

ENERGY USE
IN
ALUMINIUM INDUSTRY

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TABLE OF CONTENTS

Chapter		Page
	List of Tables	
	List of Figures	
	Summary	
1.	INTRODUCTION	1
	1.1 Study Objectives	1
	1.2 Methodology	3
	1.3 Report Structure	3
2.	INDUSTRY STATUS	5
	2.1 Background	5
	2.2 Production and Consumption Trends	8
	2.3 Consumption Pattern	12
3.	PRODUCTION OF PRIMARY ALUMINIUM	19
	3.1 Mining of Bauxite	19
	3.1.1 Bauxite Characteristics	19
	3.1.2 Mining Methods	20
	3.1.3 Location of Mines	23
	3.1.4 Transportation of Bauxite	24
	3.1.5 Energy Use in Mining	24
	3.1.6 Energy Use in Transportation	24
	3.2 Production of Alumina	26
	3.2.1 Process Description	26
	3.2.2 Materials and Energy Flows	29
	3.3 Smelting of Alumina	38
	3.3.1 Electrolysis	38
	3.3.2 Anode Preparation	39
	3.3.3 Materials and Energy Flows	40

Contd....

TABLE OF CONTENTS (continued)

Chapter	Page
4. FABRICATION OF ALUMINIUM PRODUCTS	44
4.1 Preparation of Metal	44
4.1.1 Direct Chill Casting	45
4.2 Fabrication Methods	46
4.2.1 Wrought Products	46
4.2.1.1 Rolling	46
4.2.1.2 Extrusion	47
4.2.1.3 Forging	47
4.2.1.4 Drawing	48
4.2.2 Wire Rods	48
4.2.3 Castings	48
4.3 Materials and Energy Flows	49
5. COMPARISON OF MATERIALS AND ENERGY USE IN INDIAN AND INTERNATIONAL PLANTS	57
NOTES	63
REFERENCES	64

LIST OF TABLES

Table No.		Page
1.1	Cost Structure of Indian Aluminium Producers - 1982	2
2.1	Location and Installed Capacities of Aluminium Smelters	7
2.2	Aluminium Industry: Trends in Installed Capacity, Production and Capacity Utilisation	9
2.3	Trend in Capacity Utilisation of Primary Aluminium Producers	11
2.4	Trend in Aluminium Availability	13
2.5	Projections of Aluminium Demand and Production	15
2.6	Aluminium Consumption Pattern	16
2.7	Aluminium Consumption Estimates	18
3.1	Bauxite Mining: Mine Locations, Mining Methods and Bauxite Characteristics	21
3.2	Bauxite Characteristics in Other Countries	22
3.3	Transportation of Bauxite	25
3.4	Materials Requirements in Alumina Production	30
3.5	Energy Requirements in Alumina Production - Energy Form-wise	32
3.6	Energy Requirements in Alumina Production - Enduse-wise	34
3.7	Digestion Conditions in Alumina Plants	36
3.8	Materials Requirements in Aluminium Production	41
3.9	Energy Requirements in Aluminium Production	43
4.1	Assumed Values for Scrap Generation During Aluminium Fabrication	52
4.2	Energy Requirements in Aluminium Fabrication	56

5.1 Materials and Energy Use in Indian and
International Alumina Plants 59

5.2 Materials and Energy Use in Indian and
International Aluminium Smelters..... 61

LIST OF FIGURES

Fig No.		Page
2.1	Aluminium Industry: Trends in Installed Capacity, Production and Capacity Utilisation	10
2.2	Trend in Aluminium Availability	14
3.1	Flow Diagram of Bayer Alumina Refining Process	27
4.1	Material Flows in HINDALCO's Fabrication Section	50
4.2	Material Flows in MALCO's Fabrication Section	51
4.3	Energy Flows in HINDALCO's Fabrication Section	54
4.4	Energy Flows in MALCO's Fabrication Section	55

SUMMARY

(The primary aluminium industry is one of the most energy intensive industries. The major forms of energy used are electricity, coal, fuel oil and diesel oil.) Besides, materials like petroleum coke, and coal tar pitch, which can be used as fuels, are also being consumed in large quantities. These direct and indirect energy forms together with other raw materials such as bauxite, cryolite and aluminium fluoride account for around 85 % of the total production cost of aluminium metal.

The aluminium industry in India, which began with the production of household utensils from imported sheets in the thirties, has made considerable progress in the last five decades. At present six smelters are being operated by four companies (one in the public sector and three in the private sector) with a total annual smelting capacity of 362,000 tonnes.

Aluminium is being increasingly used by the country's industries in applications such as electric transmission lines, household & consumer durables, transport, building & construction, canning & packaging etc. The consumption of aluminium has always been greater than domestic production, necessitating imports to be made from other countries.

The production of primary aluminium comprises three major steps viz., mining of bauxite, converting bauxite to alumina and converting alumina to aluminium.

All primary aluminium producers have their own captive bauxite mines. Bauxite mined in the country, though mainly of the trihydrate type, is often found mixed with varying amounts of monohydrate which is difficult to process. The silica content, which also affects the performance of the alumina plant, is also higher in Indian bauxite. In contrast, the bauxite mined in other countries is either of the trihydrate or monohydrate type with comparatively lower silica content.

Depending on the scale of mining operations, bauxite is mined by one of the following three methods - manual, semi-mechanised or mechanised. The mined bauxite is transported to the alumina plant, directly or to the railhead by aerial ropeways or by trucks. From the railhead, the bauxite is moved to the plant site by rail.

Energy in the form of diesel oil, is consumed in semi-mechanised or mechanised mining as well as in transporting the bauxite to the alumina plant. Electricity, which is mainly used for lighting, is also utilised in some mines for other purposes such as crushing bauxite and transporting it through aerial ropeways.

The Bayer process is the only process used for the manufacture of alumina in the country. Both high pressure and low pressure digesters are employed by the industry. The major raw materials consumed in the Bayer process are bauxite, caustic soda and lime. The average specific consumption of materials in Indian plants in comparison with some international plants are given below:

(tonnes per tonne of alumina)					
Raw Material	India	Australia	Guinea	Jamaica	Surinam
Bauxite	2.79	2.70	2.10	2.50	2.20
Caustic Soda	0.102	0.108	0.080	0.120	0.100
Lime	0.053	0.040	0.035	0.035	0.035

In general, the raw materials consumption in Indian plants is on the higher side compared to the plants in other countries. This is mainly due to the poor raw material quality.

The energy consumed in the alumina plant is in the form of fuel oil, coal and electricity. The average specific energy consumption figures of Indian plants in comparison with some plants in other countries are given below:

(GJ per tonne of alumina)

Energy Form	India	Australia	Guinea	Jamaica	Surinam
<u>Thermal</u>					
Calcination	5.206	5.117	5.117	5.117	5.117
Steam	14.632	15.090	13.557	16.616	13.557
<u>Electrical</u>	1.303	0.864	0.864	0.864	0.864
<u>Total</u>	21.141	21.071	19.538	22.597	19.538

The Hall-Heroult electrolytic reduction process is used for the reduction of alumina into aluminium. Both prebaked and Soderberg anodes are employed by the industry.

The raw materials consumed in the smelters are alumina, cryolite, aluminium fluoride, petroleum coke and pitch. The average raw materials consumption figures in comparison with Australian and U.S. plants are as follows:

(tonnes per tonne of aluminium)

Raw Material	India	Australia	United States
Alumina	1.94	1.89	1.93
Cryolite	0.023	0.023	0.035
Aluminium Fluoride	0.034	0.020	0.020
Petroleum Coke	0.390	0.675	0.515
Pitch	0.174	0.125	0.150

Electricity is the only direct form of energy used in smelters. The average electricity consumption per tonne of aluminium in Indian plants is around 17,580 kWh, as compared to around 15,600 kWh in the Western countries. The higher specific electricity consumption is mainly due to technological limitations and inefficient operation owing to frequent power cuts.

The molten aluminium metal obtained from the smelter is either cast into ingots, billets and continuous strips, which are used as starting materials in rolling and extrusion, or cast directly into electrical and commercial grade rods. The specific energy consumption figures per tonne of finished product for a particular unit are:

Product	Energy Consumed (GJ/tonne finished product)
Rolled Product	14.522
Extruded Product	14.512
Wire Rod	3.613

Thus, on the whole, the Indian aluminium plants consume more raw materials and energy compared to their counterparts abroad. This is partly due to the fact that the industry has to cope with poor raw materials, and inadequate and unsteady power supply.

Efforts to reduce consumption of raw materials and energy are being made by all the units, though on different scales. Because of these efforts, units like HINDALCO and INDAL have been able to reduce their raw materials and energy consumption to a considerable extent and have reached consumption levels which are nearly equal to that of the best plants abroad.

1. INTRODUCTION

The primary aluminium industry is one of the most energy intensive industries. The production of one tonne of aluminium requires twice as much energy as that required to produce one tonne of copper and about five times more than that needed to produce steel (Lal et al., 1985). The most important form of energy utilised is electricity; other forms of energy used include coal, fuel oil, light diesel oil or high speed diesel and energy-embodied materials like petroleum coke, coal tar pitch and coke.

The primary aluminium industry consumes about 3,925 million kWh of power annually, which accounts for 7.5 % of the industrial sector's total electricity consumption¹. The power cost, thus, is one of the most important variable costs in the production of aluminium. This is evident from Table 1.1 which gives the cost components for two of the primary aluminium producers in the country. It can also be seen from the table that energy and raw materials together account for around 85 % of the total production cost.

Thus, direct forms of energy as well as energy-embodied materials play a very important role in the production of aluminium. Conservation of energy and materials would, therefore, reduce the cost of production; besides, it would also reduce the amount of imports to be made in the case of petroleum coke, pitch, cryolite and aluminium fluoride.

1.1 STUDY OBJECTIVES

The objectives of the study are:

- to estimate the consumption of raw materials and energy at each stage of aluminium production for primary aluminium producers,
- to compare the use of energy and raw materials among the primary aluminium producers,

Table 1.1

Cost Structure of Indian Aluminium Producers - 1982
(percent)

	INDAL ^{1/}	HINDALCO ^{2/}
Alumina	25.17	27.11
Power	28.22 ✓	32.96 ✓
Labour	1.46	1.81
Calcined Petroleum Coke	20.50	17.38
Pitch	4.89	4.25
Fluorides	3.62	2.85
Depreciation	1.48	1.22
Others	9.85	10.88
Interest Charges	4.81	1.54
Total	100.00	100.00

1/ Indian Aluminium Company Limited

2/ Hindustan Aluminium Corporation Limited

Source: National Council of Applied Economic Research (1985),
Aluminium Industry in India - Problems and Prospects,
Vol. 2, New Delhi, p. 268.

- to identify the reasons for the variation of energy and raw materials consumption, and
- to compare energy intensity of Indian plants with international plants.

1.2 METHODOLOGY

With the above objectives in mind, a questionnaire was designed and mailed to all the primary aluminium producers. The information was collected separately for the four distinct operations in aluminium production i.e., mining of bauxite ore, refining bauxite to produce alumina, smelting alumina to produce aluminium and fabrication of aluminium products. Information was requested for a period of 5 years on annual consumption of raw materials and energy, and production of saleable products for each section of the plant. In addition, details regarding operating conditions of major energy consuming equipment such as boilers, calciners, furnaces, electrical and mechanical drives, in-plant generation of energy and utilities, and energy conservation measures implemented or planned were also asked for.

The response to the questionnaire was reasonably good. Out of the four primary producers - Bharat Aluminium Company Limited (BALCO), Hindustan Aluminium Corporation Limited (HINDALCO), Indian Aluminium Company Limited (INDAL), and Madras Aluminium Company Limited (MALCO) - responses were received from BALCO, HINDALCO and MALCO. However, some responses were inadequate in terms of required information. This inadequacy was overcome by making use of data available in the literature.

1.3 REPORT STRUCTURE

This report is divided into 5 chapters.

Following this introductory chapter, Chapter 2 gives the status of the aluminium industry. The evolution of the industry, past trends

in production and consumption of aluminium, and future prospects for aluminium have been analysed.

In Chapter 3, the different steps involved in the production of primary aluminium are explained. The energy and materials consumption at each of these steps have been estimated, and reasons for variation among the producers identified.

In Chapter 4, the energy and material flows in the fabrication of aluminium products have been worked out.

In Chapter 5, energy intensity of Indian plants are compared with that of international plants.

2. INDUSTRY STATUS

2.1 BACKGROUND

The aluminium industry in India started with the production of household utensils from imported sheets and circles. A sizeable utensils industry was built up from 1929 onwards but indigenous manufacture of aluminium metal was attempted only in 1937. A public limited company - Aluminium Corporation of India (ALUCOIN) - was formed to set up an integrated plant near Asansol in the State of West Bengal, for the manufacture of aluminium metal, utilising bauxite available from Ranchi and Palamau districts of Bihar. Production of alumina commenced in 1942 on an experimental basis and manufacture of aluminium metal on a commercial scale started in 1944. The initial installed capacities for alumina and aluminium ingot were 5,000 and 2,000 tonnes respectively² (Majumdar, 1970; Ministry of Commerce and Industry, Government of India, 1956).

Another company - Aluminium Production Company of India Ltd. - was incorporated in 1938 as a private limited company. In 1944, it was converted into a public limited company under its present name - Indian Aluminium Company Ltd. (INDAL). The company commenced operations in 1941 with the fabrication of imported ingots into sheets and circles at Belur in West Bengal. Production of aluminium from imported alumina was started in 1943 at Alwaye, Kerala with an installed capacity of 2,500 tonnes and production of alumina from indigenous bauxite in 1948 at Muri, Bihar, the installed capacity being 6,500 tonnes (Majumdar, 1970; Ministry of Commerce and Industry, Government of India, 1956).

The Hindustan Aluminium Corporation Ltd. (HINDALCO) was registered as a public limited company in December, 1958. The corporation has its own alumina plant and smelter located at Renukoot in Uttar Pradesh. Production of alumina and aluminium ingots was started in 1962. The initial installed capacities of the alumina

and ingot plants were 42,000 and 20,000 tonnes respectively (Majumdar, 1970).

The Madras Aluminium Company Ltd. (MALCO) was set up in 1960 as a public limited company. Production of alumina commenced from May, 1965 and that of ingots from June, 1965. The initial installed capacity of the smelter was 10,000 tonnes (Majumdar, 1970).

The Bharat Aluminium Company Ltd. (BALCO), a public sector undertaking incorporated in 1965, has established an integrated aluminium complex at Korba in Madhya Pradesh. The complex had been planned to produce 200,000 tonnes/year of alumina to feed the smelter having a primary metal capacity of 100,000 tonnes/year. The alumina plant was commissioned in April, 1973 and the first phase of the smelter (25,000 tonnes capacity) in May, 1975 (Department of Mines, Ministry of Steel & Mines, Government of India, 1984).

Considerable progress has been made by the Indian aluminium industry in the last five decades. At present, six smelters are being operated by the four companies which are engaged in the production of primary aluminium. The location and installed capacities of the smelters are given in Table 2.1.

The smelters at Korba, Belgaum, Renukoot and Mettur are integrated plants i.e., all process steps for conversion of bauxite ore to finished products are carried out at the same location. For the INDAL smelters at Alwaye and Hirakud, alumina is the input material. This alumina is produced from bauxite at the captive alumina plant at Muri in Ranchi district of Bihar.

The National Aluminium Company Ltd. (NALCO), another public sector undertaking established in 1981, is currently setting up an integrated aluminium plant in the State of Orissa comprising

Table 2.1

Location and Installed Capacities of Aluminium Smelters

Company	Location	Installed Capacity (tonnes/year)
Public Sector		
BALCO	Korba (Madhya Pradesh)	100,000
Private Sector		
INDAL	Belgaum (Karnataka)	73,000
	Hirakud (Orissa)	24,000
	Alwaye (Kerala)	20,000
HINDALCO	Renukoot (Uttar Pradesh)	120,000
MALCO	Mettur (Tamil Nadu)	25,000
Total		362,000

Source : Department of Mines, Ministry of Steel & Mines,
Government of India (1984), Annual Report - 1983-84,
New Delhi, p. 33.

a 800,000 tonnes/year alumina plant at Damanjodi and a 218,000 tonnes/year aluminium smelter at Angul (Department of Mines, Ministry of Steel & Mines, Government of India, 1984). The first phase of the plant is expected to go into production in early 1987.

A proposal for the setting up of a 600,000 tonnes/year alumina plant at Visakhapatnam in Andhra Pradesh in collaboration with the USSR is under consideration (Department of Mines, Ministry of Steel & Mines, Government of India, 1984).

2.2 PRODUCTION AND CONSUMPTION TRENDS

The trends in installed capacity, production and capacity utilisation are given in Table 2.2 and shown graphically in Figure 2.1. The capacity utilisation which was over 100 % in 1970-71 steadily declined to a level of around 60 % in 1974-75. The following two years saw an increase in capacity utilisation to around 79 %. Thereafter the industry's capacity utilisation declined and remained more or less stagnant in the range between 60 and 65 % upto 1983-84. The position, however, improved in 1984-85 when capacity utilisation increased to 75 %. The company-wise capacity utilisation figures are given in Table 2.3. The fluctuation in capacity utilisation for individual units as well as for the entire industry is mainly due to inadequate and irregular power supply to the plants.

The demand for aluminium has been registering a steep rise since 1977-78. The power sector alone has accounted for more than 50 % of the consumption of metal because of large outlays for transmission and distribution programmes. As the demand was more than the domestic production, imports were made initially through BALCO and later through the Minerals and Metals Trading Corporation (MMTC). However, since 1981-82 there has been a slump in demand because of two reasons - firstly, the State electricity boards who are the main consumers of the electrical conductor (EC) grade metal have not been able to place orders because of financial constraints, and secondly, the demand for commercial grade aluminium was adversely affected by the high cost of the metal. However, of late there are

Table 2.2**Aluminium Industry: Trends in Installed Capacity,
Production and Capacity Utilisation**

Year	Installed Capacity (`000 tonnes)	Production (`000 tonnes)	Capacity Utilisation (percent)
1970-71	156	167	107.1
1971-72	173	181	104.6
1972-73	195	176	90.3
1973-74	195	148	75.9
1974-75	210	127	60.5
1975-76	246	187	76.0
1976-77	266	209	78.6
1977-78	291	179	61.5
1978-79	321	214	66.7
1979-80	321	192	59.8
1980-81	321	199	62.0
1981-82	321	207	64.5
1982-83	321	208	64.8
1983-84	362	220	61.0
1984-85	362	273	75.4

Source: Financial Express (1985), "Industry Profile - Aluminium",
November 22, New Delhi.

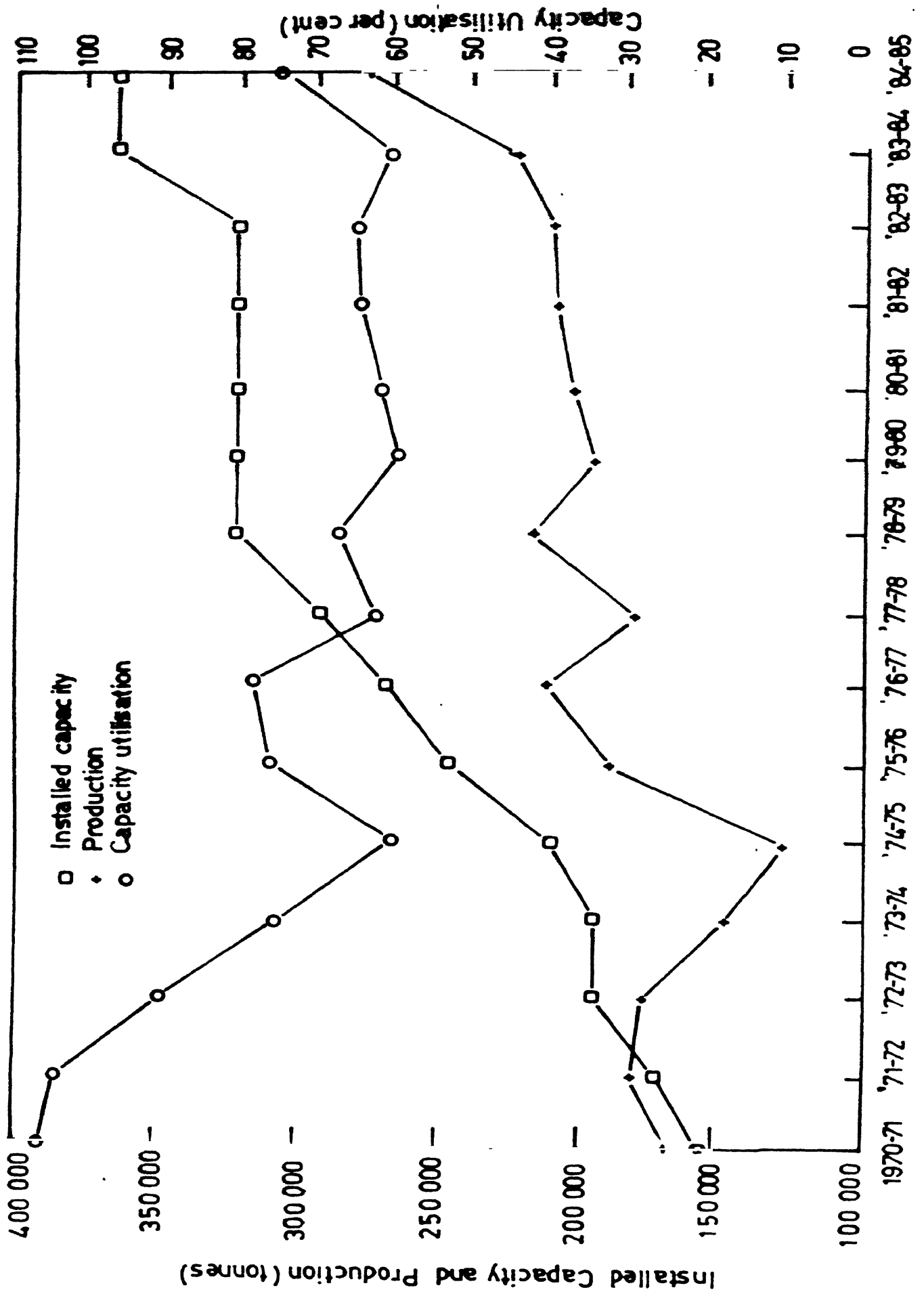


Table 2.3

Trend in Capacity Utilisation of Primary Aluminium Producers
(percent)

Company Year	BALCO	HINDALCO	INDAL	MALCO	Industry Average
1976-77	25.1	88.2	82.2	71.6	78.6
1977-78	31.6	57.8	68.5	74.9	61.5
1978-79	31.9	70.7	83.8	86.2	66.7
1979-80	30.5	71.5	66.4	88.4	59.8
1980-81	28.4	69.8	75.8	88.0	62.0
82	34.8	63.1	70.5	55.4	64.5
83	43.5	74.3	54.2	48.6	64.8
84	60.4	75.0	47.0	26.4	61.0

Source: Lal, V.B. et al. (1985), The Aluminium Industry in India - Promise, Prospects, Constraints and Impact, National Institute of Science, Technology & Development Studies, New Delhi, p.74.

some signs of revival of demand. Table 2.4 gives the availability of indigenous and imported aluminium since 1970-71 and the same is shown graphically in Figure 2.2.

The domestic aluminium scene in the coming years is likely to reverse the earlier trend of stagnancy and shortages. According to the Seventh Plan Working Group on Non-ferrous Metals (Aluminium and Magnesium), production and demand are expected to increase considerably, with demand exceeding supply till 1987-88, necessitating imports to fill this gap (Table 2.5). Thereafter NALCO is expected to come on stream, and from 1988-89, there is likely to be surplus aluminium available in the country.

However, the latest assessment by the Government has revealed that this surplus may last only for two years if the growth in demand increases at the rate of 9 % per annum during the Seventh Plan and 8.5 % per annum in the Eighth Plan as projected by the Seventh Plan Working Group on Non-ferrous Metals (Aluminium and Magnesium). In other words, there will be a shortage of aluminium by the end of the Eighth Plan, i.e. 1994-95, to the extent of 135,000 tonnes (Ganesh, 1986). It should, however, be noted that there are chances of the demand not being realised for various reasons, the main reason being the financial constraints on State electricity boards.

2.3 CONSUMPTION PATTERN

Aluminium is being increasingly used by the country's industries such as building & construction, transport, electrical appliance, canning & packaging, household & consumer durable etc. There has been a shift in the pattern of consumption of aluminium during the last three decades, as shown in Table 2.6.

In 1950, consumer durables accounted for 52 % of the aluminium consumed, followed by the electrical sector with 20 %. However in 1984 the electrical sector became the most important consumer with 50 % share and consumer durables accounted for 18 %. With massive programmes in the energy sector, the electrical sector will continue

Table 2.4

**Trend in Aluminium Availability
(tonnes)**

Year	Production	Imports	Exports	Net Availability
1950-51	4,045	10,800	-	14,845
1960-61	18,317	25,400	-	43,717
1970-71	168,784	6,386	1,177	173,993
1971-72	181,485	21,236	-	202,721
1972-73	174,774	1,664	-	167,438
1973-74	147,845	1,605	-	149,450
1974-75	126,551	2,688	11	129,228
1975-76	187,276	5,063	7,238	185,101
1976-77	208,687	336	21,720	187,303
1977-78	178,538	9,000	599	186,939
1978-79	213,729	32,185	-	245,914
1979-80	191,825	51,054	-	239,458
1980-81	199,034	117,617	-	309,139
1981-82	206,766	28,717	-	232,100
1982-83	208,144	19,256	-	227,495

Source : Lal, V.B. et al.(1985), The Aluminium Industry in India - Promise. Prospects. Constraints and Impact, National Institute of Science, Technology & Development Studies, New Delhi, p.72.

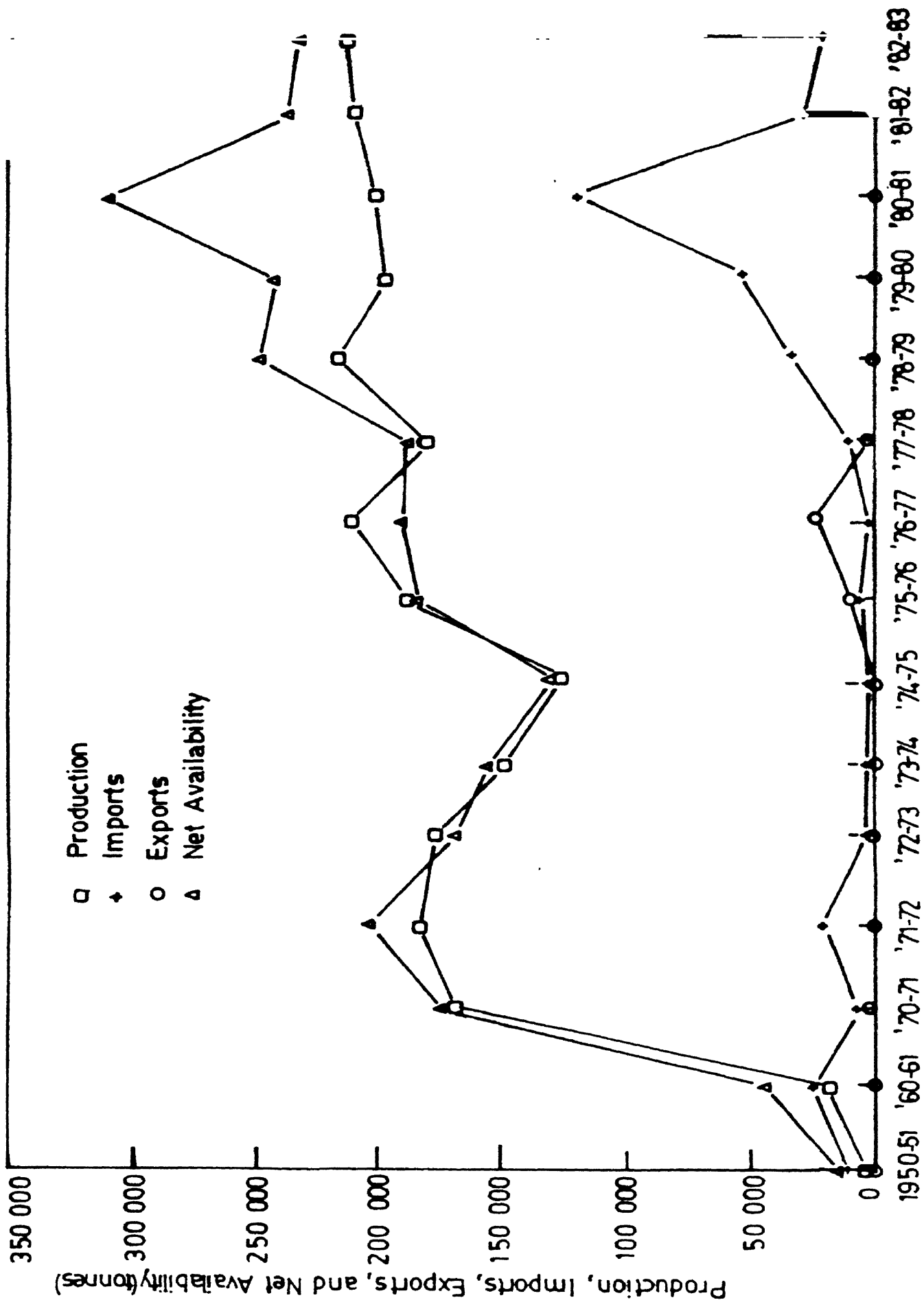


Figure 2.2 Trend in Aluminium Availability

Table 2.5

Projections of Aluminium Demand and Production
('000 tonnes)

Year	Likely Demand	Likely Production	Likely Deficit (-)/ Surplus (+)
1985-86	338	280	-58
1986-87	368	289	-79
1987-88	400	393	- 7
1988-89	436	483	+47
1989-90	475	499	+24

Source: Department of Mines, Ministry of Steel, Mines & Coal, Government of India (1985), Annual Report - 1984-85, New Delhi, p.43.

Table 2.6

**Aluminium Consumption Pattern
(percent)**

Sector	1950	1960	1970	1980	1984
Electrical	20	40	48	52	50
Household & Consumer Durables	52	24	26	18	18
Transportation	6	13	8	12	15
Canning & Packaging	10	11	8	6	7
Building & Construction	2	2	2	6	7
Miscellaneous	10	10	6	6	3
Total	100	100	100	100	100

- Sources:** 1. Lal, V.B. et al. (1985), The Aluminium Industry in India - Promise, Prospects, Constraints and Impact, National Institute of Science, Technology & Development Studies, New Delhi, p. 213.
2. Murthy, B.K. (1985), "State of Secondary Aluminium Industry in India", Proceedings of the Seminar on Conservation of Non-ferrous Metals & Energy by Recirculation, August 13-14, New Delhi, pp. 1.1 - 1.17.

to be the major consumer for the next few decades. The shares of transportation and building & construction sectors in aluminium consumption have shown moderate rise and are likely to go up further in the coming years.

The order of magnitude estimates of the consumption of aluminium in various sectors are given in Table 2.7. As figures on the total actual consumption of aluminium in the country are not available, the net availabilities given in Table 2.4 have been taken as the consumption figures. It can be observed from Tables 2.6 and 2.7 that

- though the percentage share of the electrical sector in total aluminium consumption remained more or less constant during 1970 and 1980, the actual consumption in tonnage has nearly doubled,
- the aluminium consumption in the household and consumer durables sector has shown considerable increase even though its share in total consumption has decreased from 52 % in 1950 to 18 % in 1980, and
- the consumption in the transport and building & construction sectors have increased by three and six times respectively between 1970 and 1980, in contrast to an increase of only 4 % shown in Table 2.6.

Table 2.7
Aluminium Consumption Estimates^{1/}
(tonnes)

Sector	1950	1960	1970	1980
Electrical	3,000	17,500	83,500	160,700
Household & Consumer Durables	7,700	10,500	48,700	55,600
Transportation	900	5,700	13,900	37,100
Canning & Packaging	1,500	4,800	13,900	18,500
Building & Construction	300	900	3,500	18,500
Miscellaneous	1,500	4,400	10,400	18,500
Total	14,900	43,800	173,900	308,900

^{1/} Rounded off to the nearest hundred tonnes.

3. PRODUCTION OF PRIMARY ALUMINIUM

The production of primary aluminium comprises three major steps:

1. Mining of bauxite
2. Converting bauxite to alumina, and
3. Converting alumina to aluminium.

3.1 MINING OF BAUXITE

Bauxite is the raw material used for the production of aluminium in India. India possesses one of the richest bauxite reserves in the world, amounting to 2,600 million tonnes, which account for nearly 8 % of the world's known reserves (Das Gupta, 1985).

3.1.1 Bauxite characteristics

The main constituent of bauxite is hydrated aluminium oxide. Various impurities such as silica, iron oxide etc. are also generally associated in varying degrees with hydrated aluminium oxide. The nature and extent of these impurities determine the suitability of any particular variety of bauxite for the manufacture of aluminium metal.

There are two distinct varieties of hydrated aluminium oxide - the trihydrate, $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ (gibbsite) and the monohydrate, $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ (diaspore). Although diasporic bauxites contain a larger percentage of aluminium oxide (upto 75 %) as compared to gibbsitic bauxites (50-60 %), diasporic bauxites are more difficult to process, because they are harder and not easily soluble in caustic soda in the Bayer process for the manufacture of alumina, which is the first step in the production of aluminium metal (Ministry of Commerce and Industry, Government of India, 1956).

Indian bauxite has certain chemical characteristics which are not generally found in bauxite anywhere else in the world. Bauxite occurring in other countries has, more or less, uniform characteristics. For example, in Africa and the West Indies, nearly

all bauxite is trihydrate and in Europe practically all bauxite is of the monohydrate type. In India there is no uniformity in the constituents of bauxite. Although Indian bauxite is mainly of the trihydrate type, varying amounts of monohydrate are often found mixed with the trihydrate. This lack of uniformity applies to other constituents of bauxite as well (Majumdar, 1970).

Table 3.1 shows the locations of mines, method of mining employed, and the range of mineralogical and chemical compositions of bauxite mined. The bauxite characteristics in few other countries are given in Table 3.2 for comparison.

3.1.2 Mining Methods

Mining of bauxite in India is done by the open cast method. Manual, semi-mechanised and mechanised methods are used for over-burden removal and mining of ore. The choice of mining method depends on factors such as the nature and thickness of over-burden, the scale of mining operations, prevailing labour costs etc.

In small or medium scale operations, manual mining is employed. The over-burden and the bauxite zone are dug up using picks, crowbars and spades. Where blasting is required, shallow blast holes are drilled by hand jumpers and blasted with gun powder or special gelatine. The over-burden is manually transported to the dumping area. Manual mining is generally employed in mines with an annual production of less than 20,000 tonnes.

In semi-mechanised mining, blast holes are drilled using pneumatically driven jack hammers supplied with compressed air by portable diesel engine driven compressors. Bauxite is handled and loaded manually onto trucks for transport to the plant or railhead. The over-burden is handled, transported and dumped manually. Semi-mechanised methods are employed at mines with annual production of bauxite between 20,000 and 50,000 tonnes.

In mechanised mines, the over-burden is stripped and transported using diesel dipper shovels and dumpers. Blast holes are drilled by

Table 3.1
Bauxite Mining: Location of Mines, Mining Methods and Bauxite Characteristics

Company	Location of mine	Mining method	Mineralogical composition (weight %)	Diaspore ($Al_2O_3 \cdot H_2O$)	Chemical composition (weight %)	Fe_2O_3	TiO_2	LOI ^{1/}
PILCO	Raktivedar & Narhoodadar	Mechanised	23	13	37-51	4-7	8-10	20-23
	Prutloapehar	Semi-Mechanised	Mostly Gibbsite	-	46-47	<4.5	8-10	20-23
HINDALCO	Fisher Mines	Hand-operated-Mechanised	NA ^{2/}	NA	47-52	1.75-2.75	8-12	20-25
		All others-Semi-Mechanised						
INDM	Amarkantak	Semi-Mechanised	NA	NA	50-52	3-4	8-12	20-25
INDM	Ragru Hill	Mechanised	35-36	8-9	49-50	3-4	8-10	23-25
	Pipartaswadi	Mechanised	38-42	3-4	48-52	2-4	5-7	25-27
PILCO	Shevaroy Hills & Kollu Hills	Manual	Mostly Gibbsite		46-47	~4.5	20-23	~1.5

1/ Loss on Ignition
2/ Not Available

Sources: Compiled from 1. National Council of Applied Economic Research (1983), Research and Development Linkages in Non-Ferrous Metals and Coal and Lignite Sectors, Volume 2 - Aluminium, Magnesium and Tin, New Delhi.

2. Indian Bureau of Mines (1977), Mineral Facts & Problems - Bauxite, Monograph No.5, Nagpur, p.316.

Table 3.2

Bauxite Characteristics in Other Countries

Country	Location of mine	Mineralogical composition (weight %) Gibbsite ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$)	Diaspore ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$)	Chemical composition (weight %) Al_2O_3	SiO_2 (total)	SiO_2 (residue)
Australia	Darling Ranges, Western Australia	Virtually all Gibbsite	-	30-38	20	0.5-2.5
	Weipa & Andoom, Cape York, Queensland,	NA ^{1/}	Upto 35 %	54-59	5.4-5.0	1.6-3.2
	Gove, Northern Territory	Mostly Gibbsite	-	50	3.4-4.2	<3.6
Guinea	Sangaredi	Mostly Gibbsite	-	58-60	1.5	NA
Jamaica	No specific mine	NA	Upto 20 %	50	1-3	1.5
Surinam	No specific mine	Gibbsite	-	50-60	1.6	NA

^{1/} Not Available

Source: Novelt, M.H. and Larsen, J. (1983), The World Aluminium Industry, Vol. 1, Australian Mineral Economics Pty. Ltd., Sydney.

conventional wagon-mounted drifters and rotary auger drills. After blasting, bauxite is loaded and transported using diesel dipper shovels and dumpers. Mechanised mines have annual production capacities of over 50,000 tonnes.

3.1.3 Location of Mines

All primary aluminium producers have their own captive mines. The locations of mines are given below (National Council of Applied Economic Research, 1983):

BALCO operates captive mines at

- Raktidadar and Nanhoodadar in Shahdol district of Madhya Pradesh, and
- Phutkapahar in Bilaspur district of Madhya Pradesh.

The mine at Gandhamardan in Koraput district of Orissa is being developed.

HINDALCO's sources are

- Captive mines at Birhnipat, Maidanpat, Banrobar, Shrangdag and Pakharpat in Ranchi and Palamau districts of Bihar,
- Mines of M/s. Minerals and Minerals Limited (a wholly owned subsidiary) at Manduapat, Banrobar and Salaiya in Ranchi and Palamau districts of Bihar, and
- Captive mines in the villages of Amarkantak, Dumagarh and Jaleswar in Bilaspur and Mandla districts of Madhya Pradesh.

INDAL obtains bauxite from

- Bagru hill bauxite mines near Lohardaga in Ranchi district of Bihar, and
- Ngartaswadi bauxite mines in Kolhapur district of Maharashtra.

MALCO gets its bauxite from

- Shevaroy hills and Kolli hills in Salem district of Tamil Nadu.

The mine of NALCO is being developed at Panchpatmali in Koraput district of Orissa.

3.1.4 Transportation o Bauxite

Bauxite is transported from the mines by road or aerial ropeway either to the alumina plants directly or to the railhead. Table 3.3 summarises the particulars of transportation of bauxite from mines to the consuming plants.

3.1.5 Energy Use in Mining

The forms of energy used in bauxite mining are light diesel oil (LDO) and electricity. LDO is used in mining equipment of semi-mechanised/mechanised mines such as diesel engine driven air compressors, shovels, dumpers etc. Electricity, which is mainly used for lighting purposes, is also utilised in some mines for crushing bauxite. Energy consumption is a function of the thickness of overburden and the mining method employed. Mechanised mining consumes more energy than semi-mechanised/manual mining.

Because of non-availability of adequate data, analysis of energy consumption in mines could not be carried out.

3.1.6. Energy Use in Transportation

As given in Table 3.3, the three modes of transport used for the movement of bauxite in India are road, aerial ropeway and rail. Except for the Phutkapahar (BALCO), Ngartaswadi (INDAL), and Shevaroy and Kolli hills (MALCO) mines, which transport bauxite directly to the alumina plant by road or aerial ropeway, all other mines depend on the railways for transporting bauxite.

Though some companies have their own fleet of diesel trucks for transporting bauxite by road, the general practice is to employ private contractors for this purpose. Since the companies could not compile the diesel consumption figures of these operators, the energy consumption figures were not available for this study. Besides, the breakup of the quantities of bauxite transported from individual mines were also not available. Therefore, energy consumption in transportation could not be calculated. According to Kalra (1985a),

Table 3.3

Transportation of Bauxite

Company	Location of Mines	Bauxite transported		Mode of Transport	Distance (km)
		From	To		
NALCO	Lakshadwar & Kanchadwar	Mines Choktipani	Choktipani Railhead Korba Plant	Bicable Ropeway Rail	17 190
	Phutkarpahar	Mines	Korba	Bicable Ropeway	16
	Amarkantak	Mines	Pendra Road Railhead Renukoot	Road	30 (Oct-June) 50 (July-Sept) 623
NALCO	HINDALCO Mines Division, Pichughuta	Pendra Road	Tori Railhead Tori Railhead Tori Railhead Renukoot	Road Road Road Rail	85 62 60 237
	Mines	Shrangdag Mines	Richughuta Railhead	Bicable Ropeway	8
	Mines	Maidanpat Mines	Richughuta Railhead	Road	35
	Mines	Rudnipat Mines	Richughuta Railhead	Road	42
NALCO	Minerals & Minerals Ltd., Pichughuta	Richughuta	Renukoot	Rail	217
	Barru Hill	Mines	Lohardaga Railhead Huri Alumina Plant	Monocable Ropeway Rail	10 193
	Wartawadi	Mines	Belgaum Alumina Plant	Road	58
NALCO	Chavay Hills	Mines	Mettur	Road	50
	Kolli Hills	Mines	Mettur	Road	100
	Hydore Minerals Ltd., Pyndoor	Mines	Mangalore Mettur	Road Rail	160 1/ NA
NALCO	Panchpatnali	Mines	Damanjodi	Belt Conveyor	14

1/ Not Available

Sources: Compiled from

1. Study Questionnaire Responses
2. Indian Bureau of Mines (1984), Indian Minerals Yearbook - 1981, Nagpur.
3. Indian Bureau of Mines (1977), Mineral Facts & Problems - Bauxite, Bombay Graph No. 5, Nagpur.

about 40 kg of diesel/tonne of bauxite, i.e., approximately 200 kg of diesel/tonne of hot metal, is consumed for transporting bauxite by road to a distance of 500 km. In other words, diesel consumption is of the order of 0.08 kg/bauxite tonne-km³.

Electrical energy is utilised in the aerial ropeways and is obtained either from the State electricity boards or from captive diesel generators. As in the case of road transport, the quantities of bauxite transported through aerial ropeways were not available and so the energy consumption could not be calculated.

3.2 PRODUCTION OF ALUMINA

3.2.1 Process Description

The Bayer process is the only process used for the manufacture of alumina in the country. This process has the ability to treat both trihydrate and monohydrate bauxites.

A general flow diagram for the Bayer process is shown in Figure 3.1. In this process, bauxite is crushed and ground, mixed with a solution of caustic soda (80-110 g Na₂O/litre⁴), and pumped into large pressure vessels known as digesters, where the ore is digested using steam (live steam is injected into the digester or indirect heating is employed) for approximately one hour. For monohydrate type bauxite, in which the alumina occurs in forms which are more difficult to dissolve than in trihydrate type bauxite, stronger caustic solutions (upto 220 g Na₂O/litre), higher temperatures (upto 300°C) and pressures (as high as 150 atm) and sometimes longer digestion times are required (McGraw-Hill, 1982). The caustic soda solution reacts with the hydrated aluminium oxide to form soluble sodium aluminate according to the following reaction:

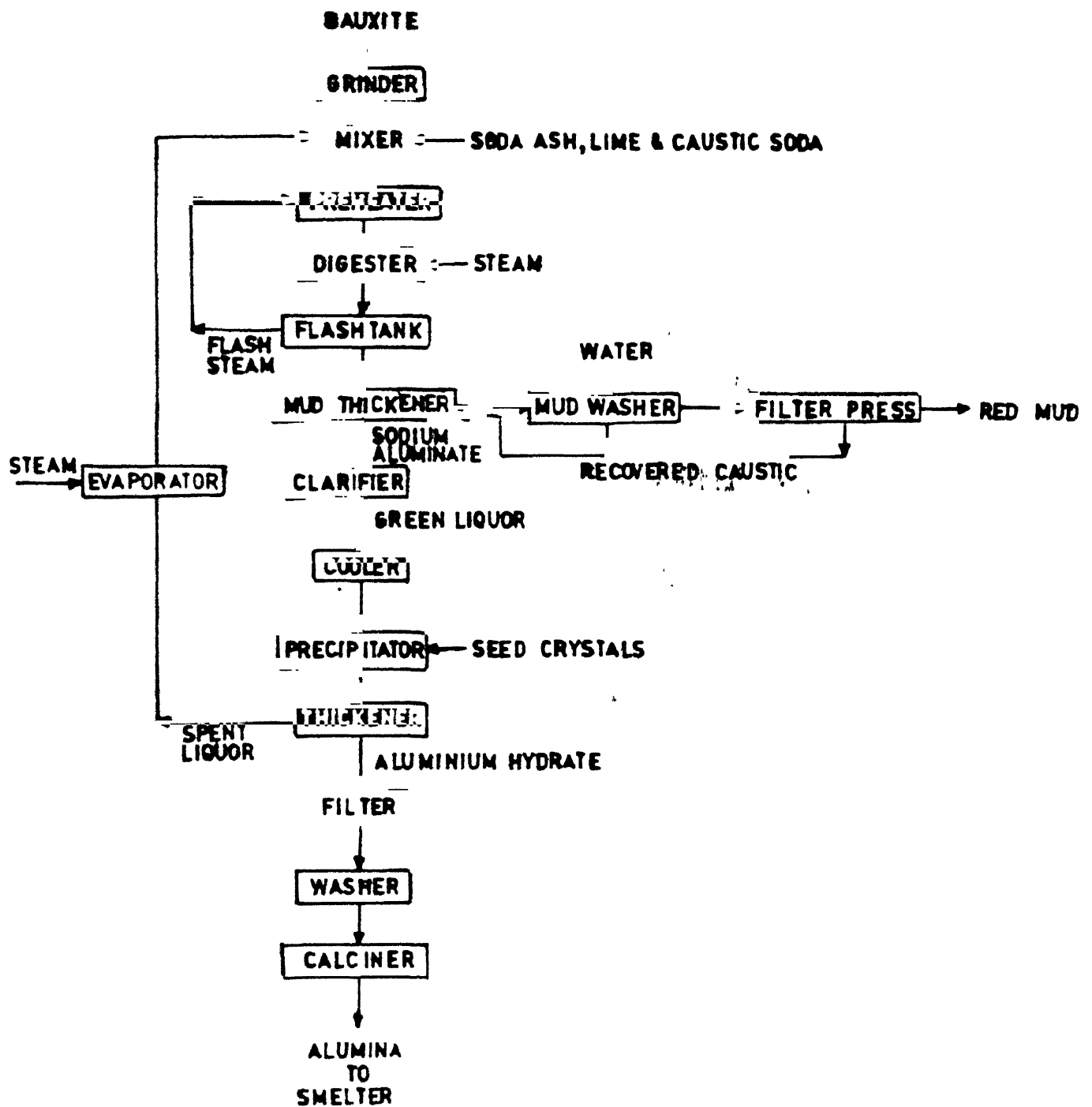
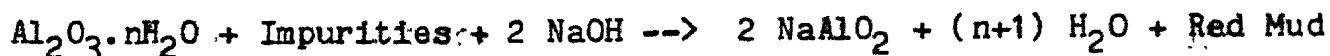
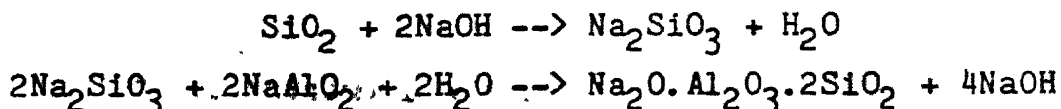


Figure 3.1 Flow Diagram of Bayer Alumina Refining Process

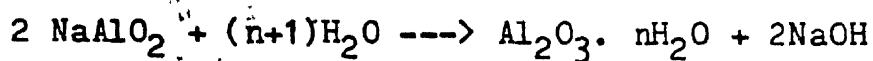


The residue, known as red mud, contains the insoluble impurities (oxides of iron, silica and titanium) and the sodium - aluminosilicate compound, referred to as desilication product, formed by the following reaction of silica in the bauxite with the sodium aluminate-caustic soda solution:



Following digestion, the caustic slurry is cooled to 120°C in a series of flash tanks. The steam flashed off during cooling is used to preheat the fresh bauxite-caustic mixture prior to its entry into the digesters. After cooling, the red mud is removed from the caustic slurry in thickeners and goes to a mud washer - filter, where the mud is washed with water to recover caustic soda, which goes back to the thickener and into the main liquor process stream.

The sodium aluminate solution goes to a clarifying filter, and this clarified solution, known as green liquor, then goes to a precipitator. The liquor is cooled to 50-60°C in a heat exchanger and placed into large precipitation vessels where it is diluted, seeded with aluminium hydrate crystals and mildly agitated to precipitate dissolved aluminium hydrate as per the reaction:



Approximately half of the aluminium hydrate is precipitated during a 34-36 hour period (Chiogioji, 1979). The resulting hydrate is separated by settling and filtration. Spent liquor goes on to a spent liquor treatment operation, and washed hydrate goes for

calcination. Spent liquor is a caustic solution containing about 50 % of the sodium aluminate originally present before precipitation. This is recycled to the process for reuse. The caustic content of this recycled liquor is increased to the desired level for digestion by evaporation of excess water and addition of makeup caustic.

The washed aluminium hydrate is calcined in long, rotary kilns at temperatures above 980°C . Free water and water that is chemically combined with the aluminium hydrate are driven off, leaving alumina, or aluminium oxide as a dry, fine white powder.

3.2.2 Materials and Energy Flows

Table 3.4 summarises the materials requirements for one tonne of alumina production in Indian plants. The specific consumption figures given in this table and in other similar tables showing materials and energy requirements are based on the annual materials consumption figures and those of alumina and aluminium production reported by the producers in response to the study questionnaire, as well as that obtained from the literature. Some data was available continuously for a few years in time series form; other data was available only for some years on an intermittent basis. The range denotes the minimum and maximum specific consumption figures over the period for which data was available, and the average is the arithmetic mean of the specific consumption figures.

The consumption of bauxite in the Bayer process is a function of the Al_2O_3 content of bauxite. Besides, it also depends on the physical and chemical losses taking place in the process. Physical losses include those that occur in the washing of crude bauxite and entrainment losses in red mud. The chemical loss, in the form of alumina, is due to the reactive silica in bauxite; the reactive silica forms sodium-alumino-silicate compound in the process when reacting with sodium aluminate-caustic soda solution (section 3.2.1). This compound, which forms part of red mud, also causes loss of caustic soda. In practice, every one gram increase of silica content in bauxite leads to a loss of 0.85-2.00 grams of Al_2O_3 and 0.5-0.7

Table 3.4

Materials Requirements in Alumina Production^{1/}
(tonnes per tonne of alumina)

Plant	BALCO		HINDALCO		INDAL (Belgaum)		INDAL (Madi)		MILCO	
	Range	Ave	Range	Ave	Range	Ave	Range	Ave	Range	Ave
Bauxite	2.40 - 2.50	2.48	2.70 - 2.85	2.78	2.80 - 3.00	2.90	3.00 - 3.10	3.05	2.66 - 2.79	2.73
Caustic Soda	0.101-0.115	0.120	0.090-0.094	0.091	0.090-0.100	0.095	0.102-0.112	0.107	0.076-0.105	0.098
Lime	0.079-0.161	0.121	0.030-0.076	0.054	0.023-0.030	0.028	0.030-0.040	0.035	0.017-0.038	0.028
Soda Ash	2/	-	0.077-0.019	0.018	-	-	-	-	-	-

1/ The figures are based on data for the periods mentioned below:

BALCO : 1977-78 - 1983-84
HINDALCO : 1977-1983
INDAL : 1983
MILCO : 1975, 1978-1984

2/ Not Applicable

Sources: 1. Study Questionnaire Responses

2. National Council of Applied Economic Research (1985), Aluminium Industry in India - Problems and Prospects, Vol.2, New Delhi.

3. Lal, V.P. et al. (1985), The Aluminium Industry in India - Problems, Prospects, Constraints and Growth, National Institute of Science, Technology & Development Studies, New Delhi.

grams of Na_2O (Indian Bureau of Mines, 1977). Thus the consumption of caustic soda is also a function of the chemical composition of bauxite. Since caustic soda is continuously recycled, only the make up for the loss of caustic soda in sodium-alumino-silicate compound has to be supplied.

In the case of HINDALCO, as can be seen from Table 3.1, the Al_2O_3 content of bauxite is high and silica content is low whereas for MALCO, even though the Al_2O_3 content is low, the silica content is mainly of the non-reactive type. Thus, bauxite consumption is lower at HINDALCO and MALCO. In the case of INDAL bauxite consumption is higher because of the low Al_2O_3 content in bauxite. The caustic soda and lime consumption figures are discussed later in this section.

The energy forms and quantities consumed for producing one tonne of alumina in Indian alumina plants are summarised by energy form in Table 3.5 and by end use in Table 3.6.

The major forms of energy used are fuel oil, coal and electricity. Fuel oil is used for firing calcining kilns. Besides calcination, some units also use fuel oil to generate the steam required for digestion and evaporation. Coal is used only for steam generation whereas electrical energy is mainly utilised for bauxite grinding.

Fuel oil consumption for alumina calcination at INDAL's Muri and Belgaum plants are the lowest and are around 110 litres/tonne of alumina. This figure has been achieved by better operation and improved heat recovery. The fuel oil consumption in calciners of other units remains at around 135 litres/tonne of alumina.

The consumption of fuel oil and coal for steam generation depends on process steam consumption which, in turn, depends on

- the digestion conditions such as pressure, temperature and digestion time, and
- the type of evaporator used in the spent liquor treatment section.

The digestion conditions in alumina plants are given in Table 3.7. The BALCO plant, which receives its bauxite supplies from

Table 3.5

Energy Requirements in Alumina Production - Energy Form-wise^{1/}
(per tonne of alumina)

Energy Form and Enduse	Units	BALCO		HINDALCO		INDAL (Belgaum)		INDAL (Muri)		NALCO	
		Range	Ave	Range	Ave	Range	Ave	Range	Ave	Range	Ave

<u>Electricity</u>											
Grinding 2/ Hydration	kWh	NA ^{3/}	NA	339-367	354	182-210	199	287-330	303	259-349	301
Calcination	kWh	NA	NA	38-40	39	32-34	33	31-36	34	26-27	26
Total	kWh	516-578	537	377-408	393	214-244	232	318-361	337	285-376	327
	GJ ^{4/}		1.933		1.415		0.835		1.213		1.177
<u>Fuel Oil</u>											
Calcination	kl	0.132-0.141 ^{5/}	0.136 ^{5/}	0.131-0.139	0.136	0.109-0.113 ^{5/}	0.112 ^{5/}	0.106-0.112	0.110	0.123-0.145 ^{5/}	0.131 ^{5/}
Steam Generation	kl	0.036-0.051 ^{5/}	0.041 ^{5/}	-	-	0.159-0.202 ^{5/}	0.185 ^{5/}	-	-	0.339-0.374 ^{5/}	0.356 ^{5/}
Total	kl	0.177	7.372	0.136	5.664	0.297	12.370	0.110	4.581	0.487	20.283
<u>Coal</u>											
Steam generation	t	0.390-0.545 ^{5/}	0.466 ^{5/}	0.850-1.120	0.970 ^{5/}	-	-	1.110-1.260	1.165	-	-
	GJ		8.765		18.246				21.914		
<u>TOTAL ENERGY CONSUMPTION</u>											
	GJ		18.070		25.325		13.205		27.708		21.460

contd...

Table 3.5 (continued)

1/ The figures are based on data for the periods mentioned below:

BALCO : 1977-78 - 1983-84
HINDALCO : 1977-1985
INDAL : 1979-1983
MALCO : 1980-1982

2/ Processes upto precipitation of alumina in Bayer Process

3/ Not Available

4/ Conversion factors:

Electricity

1kWh = 3600 kJ = 0.0036 GJ

Fuel Oil

Specific gravity = 0.94

Calorific value = 10600 kcal/kg

Coal

Calorific Value: 4500 Kcal/kg
: 18810 kJ/kg

5/ Includes fuel to generate steam consumed in anode paste preparation

6/ Not Applicable

Sources: 1. Study Questionnaire Responses

2. National Council of Applied Economic Research (1985),
Aluminium Industry in India - Problems and Prospects,
Vol.2, New Delhi.

3. Lal, V.B. et al. (1985), The Aluminium Industry in India -
Promise, Prospects, Constraints and Impact, National
Institute of Science, Technology & Development Studies,
New Delhi.

Table 3.6

Energy Requirements in Alumina Production - Enduse-wise/
(per tonne of alumina)

Enduse and Energy Form	Units	BALCO	HINDALCO	INDAL (Belgaum)	INDAL (Muri)	MALCO
GRINDING						
Electricity ^{2/}	kWh	NA ^{3/}	354	199	303	301
	GJ	NA	1.274	0.716	1.091	1.084
HYDRATION^{4/}						
Fuel oil (for steam generation)	kl	0.041 ^{5/}	6/	0.185 ^{5/}	-	0.356 ^{5/}
Coal (for steam generation)	t	0.466 ^{5/}	0.970 ^{5/}	-	1.165	-
	GJ	10.473	18.246	7.705	21.914	14.827
CALCINATION						
Electricity	kWh	NA	39	33	34	26
Fuel Oil	kl	0.136	0.136	0.112	0.110	0.131
	GJ	NA	5.805	4.784	4.704	5.550
TOTAL ENERGY CONSUMPTION	GJ	18.070 ^{7/}	25.325	13.205	27.709	21.461

Contd...

Table 3.6 (continued)

1/ The figures are based on data for the periods mentioned below:

BALCO	: 1977-78 - 1983-84
HINDALCO	: 1977-1985
INDAL	: 1979-1983
LALCO	: 1980-1982

2/ Includes electricity consumed in hydration

3/ Not Available

4/ Processes upto precipitation of alumina in Bayer process

5/ Includes fuel to generate steam consumed in anode paste preparation

6/ Not Applicable

7/ From Table 3.4

Sources: 1. Study Questionnaire Responses

2. National Council of Applied Economic Research (1985), Aluminium Industry in India - Problems and Prospects, Vol.2, New Delhi.

3. Lal, V.B. et al. (1985), The Aluminium Industry in India - Promise, Prospects, Constraints and Impact, National Institute of Science, Technology & Development Studies, New Delhi.

Table 3.7

Digestion Conditions in Alumina Plants

Plant	Temperature (°C)	Pressure (kg/cm ²)	Soda Concentration (g Na ₂ O/l)	Duration (minutes)	Alumina Extractor Efficiency (per cent)
BALCO, Korba	240	35	185	150	92
HINDALCO, Renukoot	243	36	200	90	94
INDAL, Belgaum	138-149	7.04	200	60-70	95
INDAL, Muri	130	5.63-6.33	200	1/ NA	83
MALCO, Mettur	150	5.7-5.8	200	120-150	NA

1/ Not Available

Sources: 1. Indian Bureau of Mines (1977), Mineral Facts & Problems - Bauxite,
Monograph No.5, Nagpur.

2. Private Communication to MALCO.

Raktidadar & Nanhoodadar and Phutkapahar, requires severe digestion conditions for longer durations (35 kg/cm^2 , 240°C and soda concentration of upto $185 \text{ g Na}_2\text{O/l}$) because of the high monohydrate and silica content of bauxite (Table 3.1). The consumption of caustic soda and lime are also higher in this plant because of the high silica content. In the case of HINDALCO also, as the monohydrate content is high, severe digestion conditions are required. The Muri alumina plant of INDAL is fed with bauxite from Bagru hill, and the Belgaum plant from Ngartaswadi. Though the Al_2O_3 content is more or less the same in both the places, the proportion of monohydrate is higher in bauxite from Bagru hill. Besides, the silica content is also higher. Hence, the efficiency of alumina extraction at Muri is about 83 % compared to 95 % at Belgaum. The Mettur plant of MALCO receives bauxite, mostly trihydrate, from captive mines at Shevaroy and Kolli hills, and from the Byndoor mines of Mysore Minerals Ltd. The silica content of the bauxite is mainly of the non-reactive type. This explains the low consumption of caustic soda and lime in the plant.

The steam consumption in the spent liquor treatment section varies among the plants mainly because of the different types of evaporators used. Though multiple effect evaporators are used the number of effects, i.e., number of stages of evaporation, differ from plant to plant. The evaporators with greater number of effects consume less steam for evaporating the same amount of water from spent liquor.

Steam required for digestion is generated using different fuels and at different pressures and temperatures corresponding to the operating conditions at the digesters. Hence, energy consumption for steam generation varies considerably. Electricity consumption is a function of the hardness of bauxite. Monohydrate type bauxite is harder and, therefore, consumes more electrical energy for grinding than trihydrate type bauxite. It has been estimated that monohydrate bauxite consumes about 37.5 % higher electrical energy (Gordian Associates Inc., 1974). The highest proportion of monohydrate in bauxite is at BALCO (Table 3.1). Thus the electricity

consumption at BALCO is the highest among all the plants. The electricity consumption at INDAL's Belgaum plant is the lowest among all the plants. This is due to the fact that the monohydrate content of bauxite utilised (obtained from Ngartaswadi mines) in this plant is the lowest i.e., 3-4 % (Table 3.1).

3.3 SMEETING OF ALUMINA

3.3.1 Electrolysis

The Hall-Heroult electrolytic reduction process is used for the reduction (smelting) of alumina into aluminium. In the smelter, alumina is dissolved in cells (pots) - rectangular steel boxes lined with refractory insulation that surrounds an inner container of baked carbon - containing a molten electrolyte bath consisting mostly of cryolite (sodium aluminium fluoride). The alumina content of the bath is usually maintained at 2-8 %. Excess aluminium fluoride and calcium fluoride (fluorspar) are added to lower the melting point and to improve operation.

The passage of direct current through the electrolyte decomposes the dissolved alumina. Current enters the cell through carbon anodes. Steel collector bars, joined to the carbon cathode at the bottom, conduct electric current from the cell. Aluminium metal is deposited at the cathode and therefore collects at the bottom of the cell below the cryolite bath from where it is siphoned periodically. Oxygen is released at the anodes where it reacts with carbon, forming CO and CO₂. Thus the anodes are consumed and must be replaced regularly. The smelting process is continuous. Alumina is added, anodes replaced, and molten aluminium is periodically siphoned off without interrupting current to the cells. The molten aluminium, as it comes from the cell, averages about 99.8 % purity.

Carbon anodes are hung from above the cells with their lower ends extending to within about 4 cm of the molten metal, which forms a layer under the molten bath. The heat required to keep the bath molten is generated due to the electrical resistance of the bath as

current passes through it. The amount of heat developed with a given current depends on the length of the current path through the electrolyte, that is, the anode-cathode distance, (distance between the lower end of the carbon anode and the carbon cathode block/molten metal at cell bottom) which is adjusted to maintain the desired operating temperature, usually 960-970°C. A frozen crust of electrolyte and alumina, 25-75 mm thick, forms on the top surface of the bath and on the sidewalls of the cell. Alumina is added on top of this crust, where it is preheated and dried out. While being preheated on the crust, the alumina charge serves as thermal insulation. Periodically the crust is broken and the alumina is stirred into the bath to maintain proper concentration.

The voltage at the cell terminals is 4-6 V, depending on the size and condition of the cell. In practice, large rows of smelting cells, called potlines, are electrically connected in series. A potline may consist of 50-200 cells with a total line voltage of upto 1000 V at current loads of 50,000-225,000 A.

3.3.2 Anode preparation

Because impurities in the anodes dissolve in the bath as the anodes are consumed, pure carbon (calcined petroleum coke) is used as raw material. The ground coke is mixed with enough hot coal tar pitch (steam is used to melt the coal tar pitch obtained from the coke ovens of iron & steel plants) to bond it into a block and then pressed in a mould to form the 'green' anode. This is then baked slowly at temperatures upto 1100-1200°C over a period of about 15 days. In a cavity moulded on top of each block, a steel stub is embedded by casting molten iron around it or by using a carbonaceous paste. The conducting bar is bolted to this stub. Such an electrode is termed a prebaked anode to distinguish it from the Soderberg anode, in which the electrode (single anode to a cell) is formed from a carbonaceous paste which is baked by heat from the pot as it gradually descends into the electrolyte.

The prebaked anodes have homogenous texture. They offer better electrical conductivity and hence lower anodic voltage drop, 0.3 V in prebaked anodes compared to 0.45 V in Soderberg anodes. The electrode consumption is also lower in the case of prebaked anodes (410-440 kg per tonne of hot metal) than Soderberg anodes (480-520 kg per tonne of hot metal) (National council of Applied Economic Research, 1985). Besides, in prebaked anode cells it is easy to cover the cell by means of a hood, which facilitates recovery of fluorines from the cell exhaust gases. Other advantages include easy adoptability of computer controls for crust breaking, alumina feeding, voltage control, metal tapping etc. without disturbing the pot coverings. Because of these factors, prebaked anodes are preferred for new smelter designs, even though they consume additional energy for anode baking. In India, all units except HINDALCO use Soderberg anodes.

3.3.3 Materials and Energy Flows

The materials used in the smelter are alumina, cryolite, aluminium fluoride, fluorspar (calcium fluoride) etc. The materials consumption figures for Indian smelters are summarised in Table 3.8.

The theoretical stoichiometric requirement of alumina for producing one tonne of aluminium is 1.84 tonnes (Gordian Associate Inc., 1974). However, the actual consumption in Indian plants is in the range of 1.89-2.02 tonnes. Consumption of fluorides (cryolite, aluminium fluoride and calcium fluoride) depends on the system evolved for collection and recovery of fluorides from pot room gases.

Electricity is the major source of energy utilised in the smelters. In addition to electricity, energy is also consumed in the form of energy-embodied materials such as petroleum coke, coal tar pitch and coke which are used for anode making; besides, some amount of fossil fuel is also needed for anode baking and to generate the steam required for anode paste preparation.

Table 3.8

Materials Requirements in Aluminium Production^{1/}
(tonnes per tonne of aluminium)

Plant	BALCO		HINDALCO		INDAL (Alumina)		INDAL (Bauxite)		INDAL (Huland)		NALCO	
	Range	Ave	Range	Ave	Range	Ave	Range	Ave	Range	Ave	Range	Ave
Alumina	1.94 - 1.97	1.95	1.98 - 2.02	1.99	NA ^{2/}	1.94	NA	1.91	NA	1.92	1.89 - 1.96	1.93
Cryolite	0.032-0.057	0.042	0.008-0.028	0.015	NA	0.015	NA	0.031	NA	0.020	0.008-0.029	0.016
Aluminium Fluoride	0.039-0.053	0.044	0.021-0.029	0.025	NA	0.033	NA	0.034	NA	0.033	0.033-0.040	0.036
Calcium Fluoride	NA	NA	NA	0.001	NA	0.002	NA	0.002	NA	0.033	NA	NA
Baked Anode	3/	-	0.440-0.460	0.450	-	-	-	-	-	-	-	-
Anode Paste	NA	NA	-	-	0.506-0.508 ^{4/}	0.507	0.523-0.556	0.560	0.498-0.525	0.512	0.527-0.609	0.579
					0.516-0.551 ^{5/}							

Note: 1/ The figures are based on data for the periods mentioned below:

BALCO : 1976-77, - 1983-84 (except 1979-80)

HINDALCO: 1977-1983

INDAL : 1981 (Alumina, Cryolite, Aluminium Fluoride & Calcium Fluoride)

: 1980 & 1984 (Anode paste)

NALCO : 1978-1984

2/ Not Available

3/ Not Applicable

4/ 23 KA pot line

5/ 19 KA pot line

Sources: 1. Study Questionnaire Responses.

2. National Council of Applied Economic Research (1985), Aluminium Industry in India - Problems and Prospects, Vol. 2, New Delhi.

3. Lal, V.B. et al. (1985), The Aluminium Industry in India - Problems, Prospects, Constraints and Issues, National Institute of Science, Technology & Development Studies, New Delhi.

4. Indian Bureau of Mines (1984), The Minerals Yearbook - 1981, Nagpur.

Table 3.9 summarises the energy consumption figures for Indian smelters. Electricity consumption in the smelters depends on factors such as cell design, bus-bar design and operating conditions. HINDALCO and INDAL have, over the years, optimised their operating conditions and have attained average annual operational efficiency in power consumption (ratio of standard power consumption as per the project report to actual consumption) of 88-89 % (sometimes even higher than 90 %). BALCO and MALCO have not fared so well mainly due to unavailability of adequate and steady power. BALCO has generally been operating at around 84 % and MALCO in the region of about 80 % (Lal et al., 1985).

Table 3.9

Energy Requirements in Aluminium Production^{1/}
(per tonne of aluminium)

Plant	Units	NALCO		HINDALCO		INDAL (Alusaya)		INDAL (Belgaum)		INDAL (Hirakud)		HILCO	
		Range	Ave	Range	Ave	Range	Ave	Range	Ave	Range	Ave	Range	Ave
SMELTER													
Electricity	kWh	17202-20610 ^{2/}	19107	16450-16706	16565	1) 17960-18071 ^{3/} 11) 16025-17520 ^{4/}	18016 16773	16300-17820	17060	16010-17850	16920	18665-20862 ^{2/}	19620
ANODE PLANT													
Electricity	kWh	NA ^{5/}	NA	104-125	112	NA	NA	NA	NA	NA	NA	NA	NA
Coal for steam	t	NA	NA	0.063-0.078	0.068	6/	•	7/	-	•	•	-	-
Fuel oil for steam	kl	NA	NA	-	-	•	•	NA	NA	•	•	NA	NA
Fuel oil for bldg	kl	-	-	0.081-0.124	0.110	•	•	-	-	•	•	-	-

1/ The figures are based on data for the periods mentioned below:

NALCO : 1977-78 - 1983-84
HINDALCO : 1977-1983
INDAL : 1970-1983
HILCO : 1970-1982

2/ Includes electricity used in anode preparation.

3/ 23 KA pot line

4/ 40 KA pot line

5/ Not Available

6/ Fuels used and consumption not available

7/ Not Applicable

Source: 1. Response to the study questionnaire

2. National Council of Applied Economic Research (1985), Aluminium Industry in India - Problems and Prospects, Vol. 2, New Delhi.

3. Lal, V.R. et al. (1984), The Aluminium Industry in India - Problems, Prospects constraints and Remedies, National Institute of Science Technology & Development Studies, New Delhi.

4. FABRICATION OF ALUMINIUM PRODUCTS

The 99 + % pure molten aluminium metal obtained from smelters is combined with some amount of recycled scrap, alloyed, treated and processed into finished or semifinished products. The various processing operations performed after electrolytic reduction are:

- Preparation of hot metal
- Casting of ingots, billets or wire rods
- Fabrication of finished/semifinished products by rolling, extruding, forging, drawing etc.

4.1 PREPARATION OF METAL

Molten aluminium metal is siphoned from smelting cells into large crucibles and transferred to oil-fired melting and holding furnaces for further refining or alloying with other metals. The charge to the melting and holding furnace usually includes in-plant scrap or purchased scrap alongwith enough primary metal to provide composition control. Scrap recycling provides a valuable source of aluminium at a much lower energy expenditure than that required for primary metal⁵. After remelting, the molten aluminium alloy is treated to remove dissolved hydrogen, oxides formed during remelting ("skim" or "dross"), and undesirable elements such as sodium. After appropriate treatment of the melt, the metal is cast into ingots or billets by the direct chill (DC) process, or into a continuous coiled strip by the continuous casting process. For the manufacture of electrical grade (EG) and commercial grade (CG) rods, the molten metal is directly transferred to the casting machine.

Oil-fired reverberatory hearth furnaces are utilised to prepare the metal for fabrication. These furnaces are chambers constructed of high temperature refractories. Heat transfer to the metal is

provided by a combination of radiation from the combustion products and radiation from the roof and walls. Flame impingement with the molten metal is usually avoided. The furnace operates in a cyclical manner. Metal (pure metal from the smelter as well as recycled scrap) is charged to the furnace; melting takes about three to six hours. After the charge is melted, the fuel firing rate is reduced to a level which keeps the metal in molten state. The length of this holding period depends on coordination between the melter operation and downstream processes.

4.1.1 Direct Chill Casting

Most of the ingots and billets for fabrication are cast by the direct chill (DC) process. This is accomplished on a semi-continuous basis in vertical casting and on a continuous basis in horizontal casting. The liquid metal is poured into a water-cooled mould with a bottom block which can be lowered. After the metal in the mould reaches a definite height, the bottom block is lowered at a constant rate equivalent to the liquid metal flow. The cross-section of the casting is determined by the shape of the mould which may be rectangular for rolling or forging ingot and round for extrusion billet. The continuous removal of the ingot from the mould is possible because a skin solidifies on the first contact of the metal with the mould wall, forming a shell to hold the liquid metal. Before exiting the mould, the shell pulls away from the mould wall because of the contraction which takes place during solidification. The direct chill is applied just below the mould exit by spraying water against the ingot surface. The water-cooling of the mould and spraying of water on the hot ingot cause very rapid solidification. In the case of vertical casting, ingot length is limited by the depth to which the platform can be lowered. In horizontal casting, much longer ingots can be cast and by sawing the ingot while casting is in progress, the process can be made continuous.

4.2 FABRICATION METHODS

Aluminium alloys are fabricated into three general classes of materials:

- wrought forms produced by rolling, extruding, forging or drawing;
- wire rods; and
- castings.

4.2.1 Wrought Products

4.2.1.1 Rolling

Materials produced by rolling are in the form of

- plates (more than 4 mm thick),
- sheets (0.15 - 5.60 mm thick), and
- foils (less than 0.15 mm thick).

Overlap between plates and sheets is in the range 4.0 - 5.6 mm.

The starting material in the rolling process is either the ingot cast by the DC process or the continuous strip cast by the continuous casting process.

For rolling mills with ingots as the input material, the production process starts with scalping of the ingots on the major surfaces, and sometimes on the sides also, to remove oxide film, surface irregularities, and non-uniform and segregated alloying elements. After scalping, the ingots are sent to electric resistance heated soaking pits for preheating, soaking and homogenising, to achieve uniformity of chemical composition and uniform dispersion of alloying elements in solid solution apart from imparting workability during rolling operation. The ingots, generally 125-400 mm thick, are then fed into a two high or four high reversing mill that repeatedly rolls the ingot. By successively passing between the rolls, the gaps between which is reduced after each pass, the metal is normally reduced to 5 mm or even less. The extent of reduction per pass and also the number of passes are governed by the mill power and the alloy being rolled. The strip is finally cut in the form of plates or coiled to provide feedstock to the subsequent cold rolling

operation, which may be in multistand continuous mills or single stand mills. The material is then heat treated in an electric resistance heated annealing furnace to obtain the final finished product.

In the case of mills which use continuous strip as starting material, the continuous strip, usually 5-10 mm thick, obtained from the continuous casting machine is first cooled down to the ambient temperature. The strip is then cold-rolled on a two high or four high reversible or non-reversible mill to the required thickness. Intermediate annealing may be required to facilitate rolling and obtain the required hardness of the product. This process has the advantage of producing the coiled strip directly from molten metal and therefore provides a less capital intensive option because it eliminates the operations of ingot casting, scalping, preheating, soaking, homogenising and hot rolling. The added advantages of this process are finer grain products and comparatively much less energy requirements.

4.2.1.2 Extrusion

The starting material for extrusion is the billet (150-200 mm in diameter and a maximum length of 4000 mm). The billets are heated in oil-fired or electric induction or electric resistance heated furnaces. The temperature of the billet is maintained between 480°C and 550°C depending on the alloys and sections to be extruded. The preheated billets are forced hydraulically through a preheated die assembly. The shape of the die opening conforms to the desired cross section of the product. The extruded sections are then water and/or air quenched to get the desired hardness and stretched in a stretching machine to remove the bends and twists. Finally the sections are cut to the desired lengths.

4.2.1.3 Forging

Forgings are produced by pressing or hammering aluminium alloy ingots or billets into rectangular or round shapes on flat dies, and into

complex forms in cavity dies. Depending on the alloy and type of forging, metal temperatures are generally maintained in the range of 315-470°C. Mechanical presses (capable of forces upto 16,000 tonnes) or hydraulic presses (upto 75,000 tonnes) are used in forging.

4.2.1.4 Drawing

Aluminium alloys can be drawn into pots, pans etc. by forcing sheet or foil into cavities of the desired shape. Other drawn products such as wire, tube etc. are produced by pulling rolled or extruded stock through dies.

4.2.2 Wire Rods

The electrical conductor (EC) and commercial grade (CG) wire rods are manufactured by the Properzi process. This process involves continuous casting and rolling. The molten metal is cast against a notch machined in the circumference of a large rotating water cooled wheel that serves as a mould. The cast bar is then rolled into wire rods in a rolling mill while still hot.

4.2.3 Castings

Castings are generally produced by small scale secondary aluminium producers. In casting, molten metal is poured (sand casting and permanent mould casting) or forced by pressure (die casting), into a mould, where it solidifies into the shape determined by the mould.

Die casting is best suited for high production rates and is used mostly for small parts. Good accuracy of dimension and surface finish can be obtained through die casting. The die casting process generally produces the product in its final form directly.

Permanent mould casting is similar to, but slower than, die casting. The castings produced are not as prone to porosity from entrapped gases as in die casting. It is suited to large production runs of medium size castings.

Sand casting is the most versatile method and is used for large parts whose production quantities are small.

4.3 MATERIALS AND ENERGY FLOWS

During fabrication metal losses take place at every stage. They are in the form of

- "skim" or "dross" in melting and holding furnaces, soaking pits, homogenising furnaces and billet heaters, and
- process scrap in rolling, extrusion, drawing and casting.

In the melting section, primary metal from the smelter alongwith recycled scrap is melted in an oil-fired furnace. The major cause for metal loss in the melting section is the formation of dross in the furnace. Dross generation of upto 5 % of the throughput to the furnace has been reported in the literature and the average metal content of dross is about 30 % (Kalra, 1985b).

In the fabrication section, metal loss is in the form of process scrap generated which is normally recycled by the units themselves. The average amounts of scrap generated are given below (Kalra, 1985b; Ramasubramanian, 1985):

Product	Process scrap generated (%)
Rolled products	30
Extruded products	25
Wire rods	2

The material flows per tonne of finished product in the rolling, extrusion and Properzi sections of HINDALCO, and the extrusion and Properzi sections of MALCO are given in Figure 4.1 and Figure 4.2 respectively. The scrap generation figures reported in the literature were utilised wherever necessary information was not available. The scrap generation figures assumed for calculating the material flows are given in Table 4.1. Scrap generation during ingot and billet casting has been assumed to be 4 % based on the value reported by one of the primary producers. Besides, it has also been

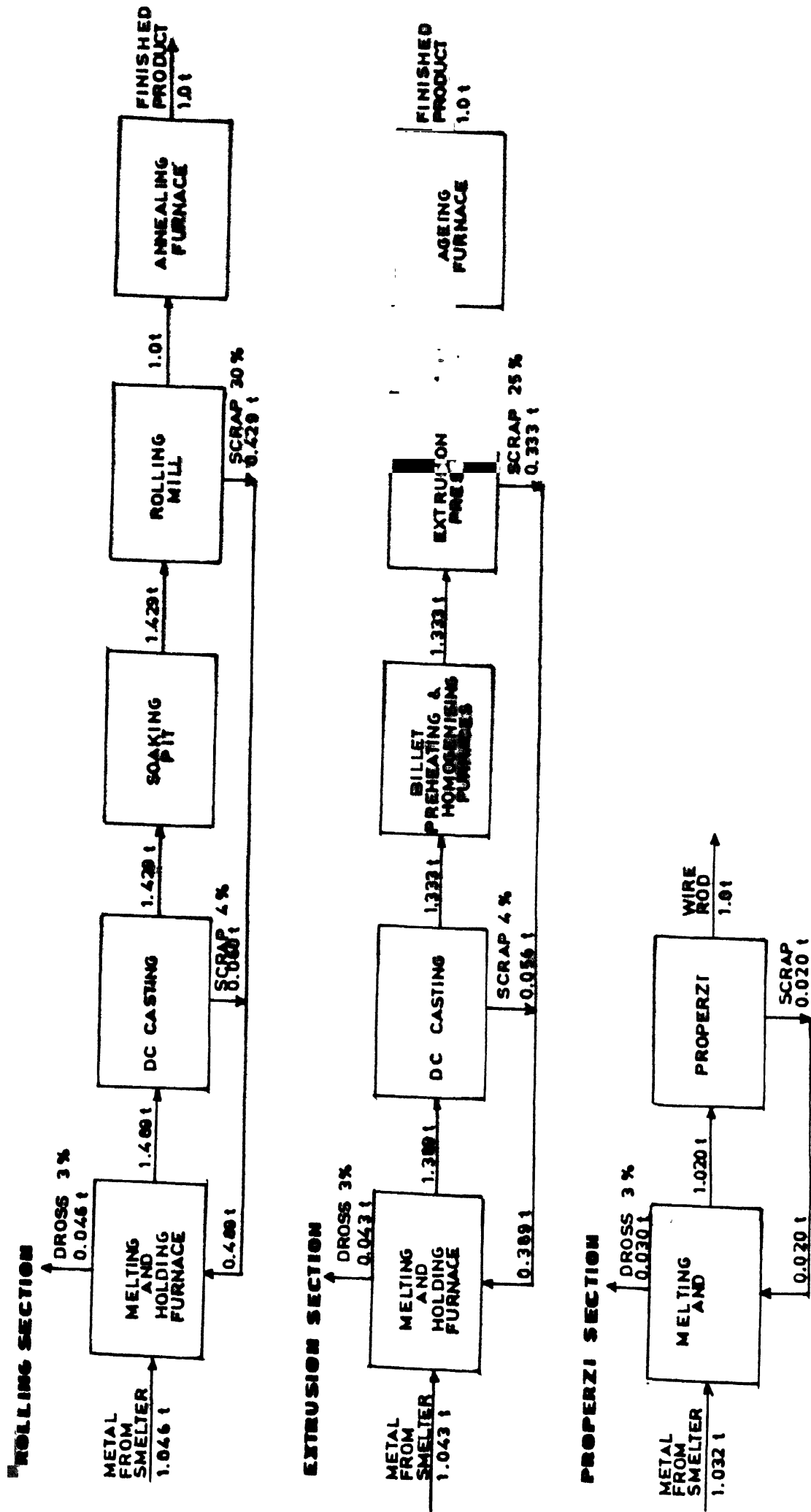


Figure 4.1 Material Flows in HINDALCO's Fabrication Section

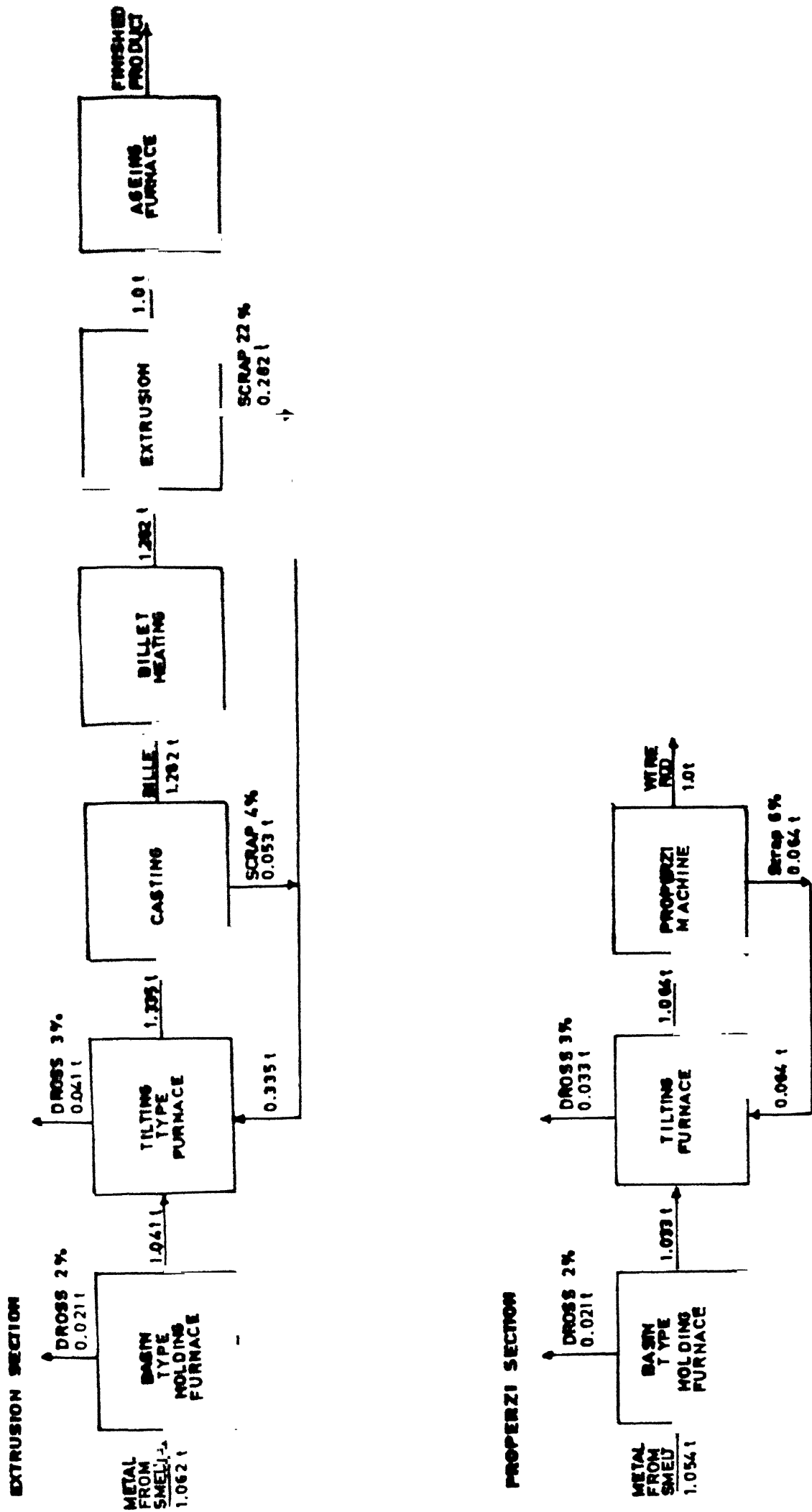


Figure 4.2 Material Flows in MALCO's fabrication section

Table 4.1

Assumed Values for Scrap Generation during Aluminium Fabrication

Product & Fabrication Stages	Scrap Generated (% of throughput)	
	HINDALCO	NALCO
1. Polled Products		
Melting and Holding Furnace	3.0 ^{1/}	- ^{2/}
Ingot Casting	4.0	-
Rolling Mill	30.0	-
2. Extruded Products		
Melting and Holding Furnace	3.0 ^{1/}	4.4 ^{3/}
Billet Casting	4.0	4.0
Extrusion Press	25.0	22.0
3. Wire Rods		
Melting and Holding Furnace	3.0 ^{1/}	4.4 ^{3/}
Properzi Machine	2.0	6.0

1/ Dross

2/ Not Applicable

3/ Weighted value based on 2 % in Basin type holding furnace and 3 % in Tilting type melting furnace.

Sources: Compiled from

1. Study Questionnaire Responses
2. Kalra, G.D. (1985b), "Aluminium Scraps in India - Demand and Supply", Proceedings of the Seminar on Conservation of Non-ferrous Metals & Energy by Recirculation, August 13 - 14, New Delhi.
3. Ramasubramanian, T. (1985), "Non-ferrous Scraps in India - Generation and Utilisation", Proceedings of the Seminar on Conservation of Non-ferrous Metals & Energy by Recirculation, August 13 - 14, New Delhi.

assumed that there is no scrap generation in the ingot/billet preheating stage and in the product heat treating stage.

The energy flows for HINDALCO and MALCO, based on the specific energy consumption figures reported in the responses to the study questionnaire and the material flows given in Figure 4.1 and Figure 4.2, are given in Figure 4.3 and Figure 4.4 respectively. Table 4.2 summarises the energy consumption in the fabrication sections of HINDALCO and MALCO.

The energy flows in the fabrication section cannot be generalised for the whole industry. This is because of the fact that the product mix as well as the amount of scrap utilised varies from unit to unit. In addition, each unit has a different line-up of furnaces, i.e., for the same application (e.g., billet heating) the units can have either an electrically heated furnace or an oil-fired furnace.

Analysis of energy and materials flows in the forging, drawing and casting sections were not carried out as none of the primary aluminium producers in the country are engaged in these areas.

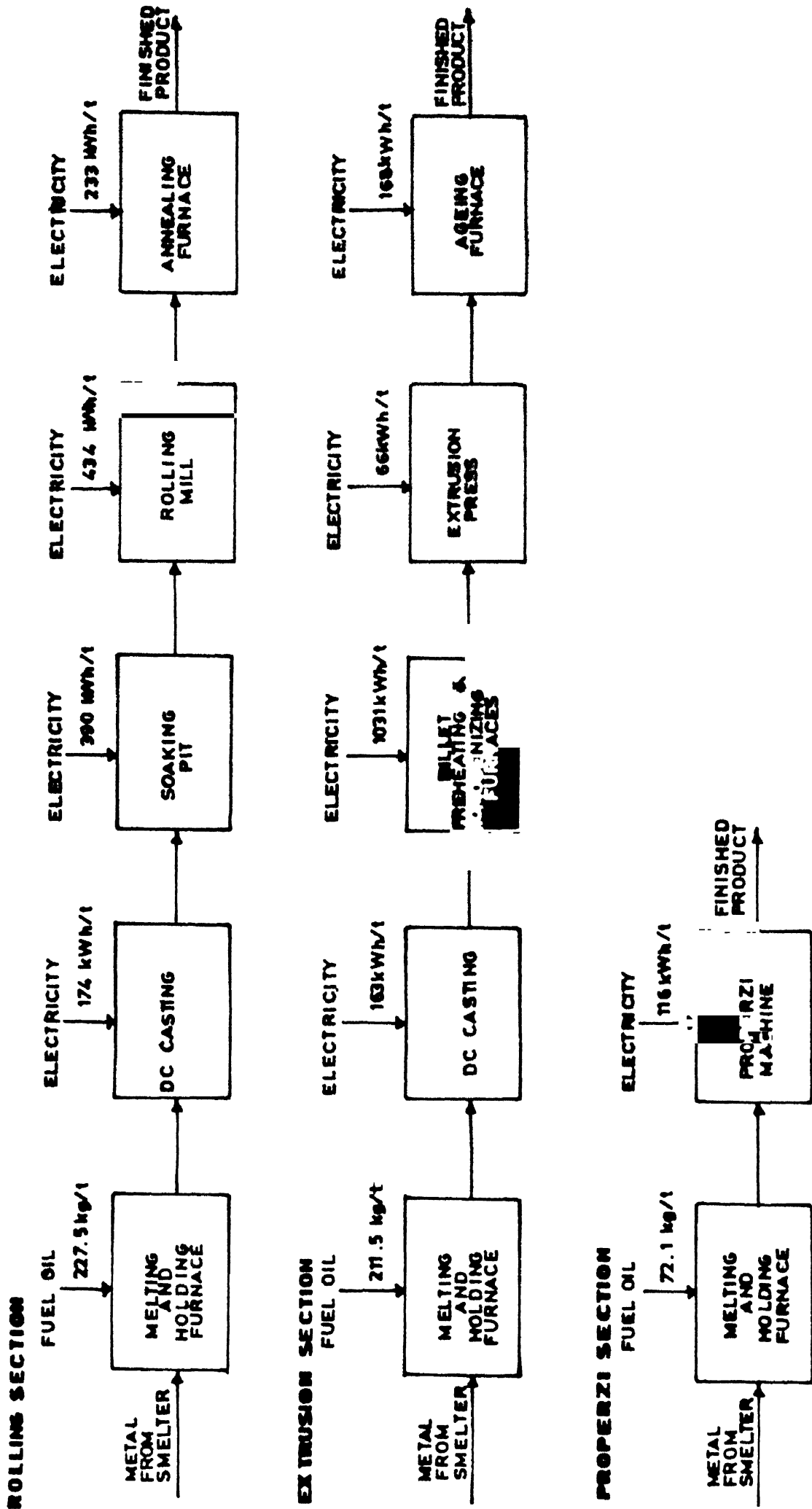


Figure 4.3 Energy flows in HINDALCO's Fabrication Section

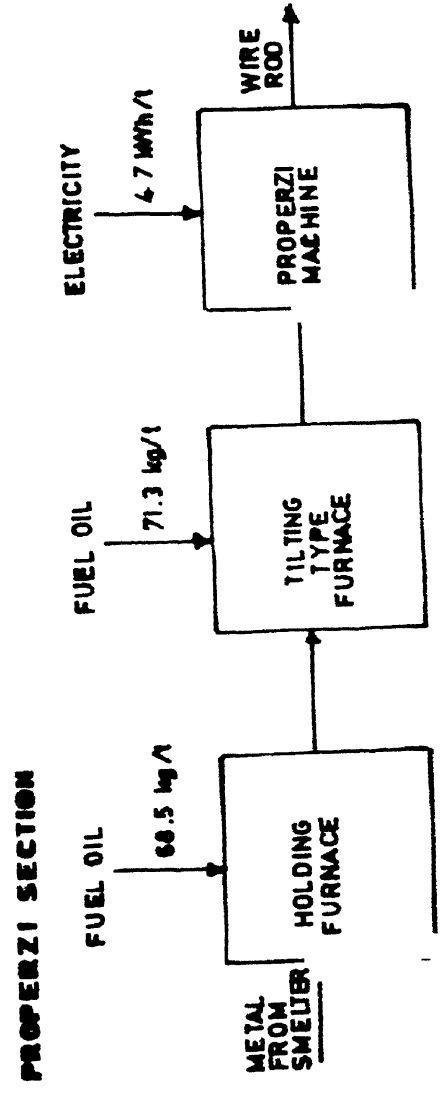
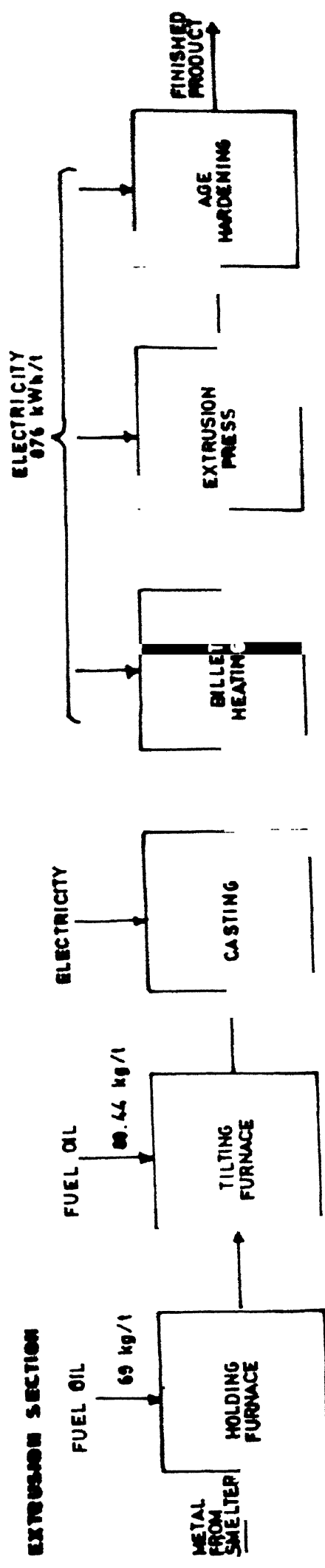


Figure 4.4 Energy Flows in MRLCO's Fabrication Section

Table 4.2

Energy Requirements in Aluminium Fabrication^{1/}
(per tonne of finished product)

	HINDALCO			NALCO		
	Fuel Oil (kg)	Electricity (kWh)	Total ^{2/} (GJ)	Fuel Oil (kg)	Electricity (kWh)	Total (GJ)
Rolling						
1. Metal Preparation and Ingot Casting	227.48	174	10.706	3/	-	-
2. Rolling Section	-	1060	3.816	-	-	-
Total	227.48	1234	14.522	-	-	-
Extrusion						
1. Metal Preparation and Billet Casting	211.50	163	9.958	158.44	NA ^{4/}	NA
2. Extrusion Section	-	1265	4.554	19.23	876	4.006
Total	211.50	1428	14.512	177.67	NA	NA
Properzi						
1. Metal Preparation	72.10	-	3.195	139.8	-	6.194
2. Properzi Machine	-	116	0.418	-	47	0.169
Total	72.10	116	3.613	139.8	47	6.363

contd..

(Table 4.2 contd.)

1/ The figures are based on data for the periods mentioned below:

HINDALCO: 1978 - 1983

MALCO : 1978 - 1982

2/ Conversion factors:

Electricity

1kWh = 3600 kJ = 0.0036 GJ

Fuel Oil

Specific gravity = 0.94

Calorific value = 10600 kcal/kg

= 44308 kJ/kg

Coal

Calorific Value = 4500 kcal/kg

= 18810 kJ/kg

3/ Not Applicable

4/ Not Available

Source: Study Questionnaire Responses.

5. COMPARISON OF MATERIALS AND ENERGY USE IN INDIAN AND INTERNATIONAL PLANTS

Having worked out the material and energy consumption figures for Indian primary aluminium producers, comparison of Indian figures with that of other countries has been carried out for the two major energy consuming sections of an aluminium plant i.e., alumina plant and aluminium smelter.

The average material and energy consumptions for Indian plants were worked out based on the latest available data from BALCO, HINDALCO, and MALCO, the data utilised being for the period 1975-1984. As explained earlier, the data was not in time series form and was of intermittent nature. The materials and energy consumption for Australia, Guinea, Jamaica and Surinam were obtained from Govett and Larsen (1983) and that for U.S. from Sin-yan Shen (1981) and Gordian Associates Inc. (1974). The figures reported by Govett and Larsen were for the year 1975. The U.S. numbers were estimated from the pre-1974 data given by Gordian Associates Inc. and the 1980 figures given by Sin-yen Shen.

Tables 5.1 and 5.2 compare the materials and energy use in Indian and international plants. While comparing the performance of Indian plants with those in other countries, the following points should be kept in mind:

- (i) Internationally, the quality of raw material used is superior. For example, the alumina plants in Australia, Guinea and Surinam use bauxite which is predominantly of the trihydrate type, whereas in India it is often mixed with varying amounts of monohydrate.
- (ii) The scale of operation is also much larger. Internationally, the sizes of the alumina plant and the smelter are in the region of 500,000 - 600,000 tonnes/year and 150,000 - 200,000 tonnes/year respectively. Compared to this, the maximum sizes in India are 200,000 tonnes/year in the case of alumina plant (BALCO) and 120,000 tonnes/year in the case of smelter (HINDALCO).

Table 5.1

Materials and Energy Use in Indian and International Alumina Plants
(Per tonne of alumina)

Input Item	Unit	India		Australia ^{1/}		Guinea ^{2/}		Jamaica ^{2/}		Surinam ^{2/}		United States	
		Range	Ave ^{3/}	Range	Ave	Range	Ave	Range	Ave	Range	Ave	Range	Ave
Materials													
Bauxite	t	2.48-3.05	2.79	2.30-3.30	2.70	2.00-2.20	2.10	2.40-2.60	2.50	2.10-2.30	2.20	2.29-2.86	2.
Caustic Soda	t	0.091-0.120	0.102	0.100-0.120	0.108	0.07-0.09	0.080	0.11-0.13	0.120	0.09-0.11	0.100	0.047-0.066	0.
Lime	t	0.028-0.121	0.053	0.03-0.05	0.040	0.02-0.05	0.035	0.02-0.05	0.035	0.02-0.05	0.035	0.014-0.047	0.
Energy													
Thermal													
Steam	GJ ^{5/}	7.705-21.914 ^{6/}	14.632	13.560-16.620 ^{7/}	15.090	12.027-1508 ^{7/}	13.557	15.087-18.146 ^{7/}	16.616	12.027-15.087 ^{7/}	3.557	NA ^{8/}	15
Calcination	GJ	4.581-5.664	5.206	4.220-6.014	5.117	4.220-6.014	5.117	4.220-6.014	5.117	4.220-6.014	5.117	NA	4
Electrical													
Electricity kWh		232-537	362	NA	240 ^{2/}	NA	240	NA	240	NA	240	NA	
GJ	-		1.3032	-	0.864	-	0.864	-	0.864	-	0.864	NA	

Table 5.1 (continued)

1/ Based on the consumption in the period 1973-1977

2/ Estimated by Govett and Larsen

3/ Arithmetic Average

4/ Mid-point of the range

5/ Conversion factors

		India	USA	Other countries
Coal	kJ/kg	18810	NA	27852
Fuel Oil	kJ/l	41650	NA	34815
Electricity	kJ/kWh	3600	NA	3600
Natural Gas	kJ/m ³	-	NA	37250

6/ Calculated from fuel consumption figures.

7/ As reported by Govett and Larsen. Fuel-wise break-up not available.

8/ Not Available.

Sources: Estimated from

1. Study Questionnaire Responses

2. Govett, M.H. and Larsen, J. (1983), The World Aluminium Industry, Vol.1, Australian Mineral Economics Pty. Ltd., Sydney.

3. Sin-yan Shen (1981), Energy and Materials Flows in the Production of Primary Aluminium, Argonne National Laboratory, Argonne, Illinois.

Table 5.2

Materials and Energy Use in Indian and International Aluminium Smelters
(per tonne of aluminium)

Input	Unit	India		Australia		United States	
		Range	Ave ^{1/}	Range	Ave ^{2/}	Range	Ave ^{2/}
Materials							
Alumina	t	1.02-1.99	1.94	NA	1.89	1.91-1.95	1.93
Crucible	t	0.015-0.042	0.023	0.020-0.025	0.023	0.020-0.050	0.035
Alumina-Fluoride	t	0.025-0.044	0.034	0.015-0.025	0.020	0.010-0.030	0.020
Petroleum Coke	t	0.387-0.424 0.343-0.411	0.406 ^{3/} 0.373 ^{4/}	0.650-0.700	0.675 ^{3/}	0.430-0.600	0.515
Pitch	t	0.116-0.215 0.142-0.158	0.200 ^{3/} 0.148 ^{4/}	0.100-0.150	0.125 ^{3/}	0.100-0.200	0.150
Energy							
Electricity	kwh	16677-10620	17580 ^{5/}	NA ^{6/}	NA	NA	NA

- 1/ Minimum of the range
- 2/ Arithmetic average
- 3/ Crucible anode
- 4/ Isolated anode
- 5/ Includes electricity used in anode preparation
- 6/ Not Available

Sources: Estimated from

- 1. Study Questionnaire Responses
- 2. Covett, R.B., and Larsen, J. (1983), The World Aluminium Industry, Vol. 1, Australian Mineral Economics Pty. Ltd., Sydney.
- 3. Sin-va Chen (1981), Energy and Materials Flows in the Production of Primary Aluminium, Argonne National Laboratory, Argonne, Illinois.

(iii) With regard to energy supply, the Indian plants face frequent power cuts and thus operate at less efficient modes leading to higher power consumption. Interruption or reduction in power supply to the cells leads to the solidification of electrolyte and metal, and the extent of solidification is a function of the duration and the nature of the power cut. When normal power is restored, additional power is to be spent for remelting and heating up of the partly or fully solidified electrolyte and metal. Besides production loss and higher specific power consumption, power cuts also lead to increased anode, cathode and bath material consumption.

NOTES

1. Based on figures from Central Electricity Authority (1986), Public Electricity Supply - All India Statistics (1982-83), New Delhi.
2. The manufacturing facilities of ALUCON (smelter capacity: 9,000 tonnes/year) were closed in 1973 because of continuing financial and other constraints. The Government of India assumed management of this unit effective from 1st May, 1978 and nominated Bharat Aluminium Company Limited (BALCO) to manage this unit. BALCO has since brought into operation the fabrication facilities; recommissioning of smelter potlines is still under consideration. This unit has been nationalised with effect from 2nd June, 1984 and has been renamed as Bidhanbag unit of BALCO (Department of Mines, Ministry of Steel & Mines, Government of India, 1984; Financial Express, 1985; Department of Mines, Ministry of Steel, Mines & Coal, Government of India, 1985).
3. According to a study carried out by the National Institute for Training in Industrial Engineering (NITIE), the fuel consumption of trucks moving loads on well paved level roads is of the order of 400 kcal/tonne-km i.e., 0.038 kg diesel/tonne-km (Planning Commission, Government of India, 1980). Thus consumption of 0.08 kg diesel/tonne-km may appear to be on the higher side. However, it should be remembered that the roads used for bauxite transportation generally pass through hilly terrain with ill-paved roads.
4. Caustic soda concentration is generally specified in terms of %Na₂O or g Na₂O/litre. Stoichiometrically,, 77.47 g of Na₂O contains the same amount of Na as 100 g of pure NaOH. Thus, an NaOH solution containing 100 g NaOH/litre is equivalent to a solution containing 77.47 g Na₂O/litre and is specified as 77.47 % Na₂O solution (Considine, 1974).
5. Recycling of scrap to make aluminium metal requires only 2,000-2,500 kWh of power per tonne compared to the total energy requirement of 40,000-50,000 kWh per tonne (including electricity, coal, oil, and carbon) for metal produced from ore. Thus the metal obtained from scrap needs only 5 % of the energy consumed to produce primary metal from ore (Murthy, 1975).

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